PALEOENVIRONMENTS, COAL PROPERTIES, AND THEIR INTERRELATIONSHIP IN PAPAROA AND SELECTED BRUNNER COAL MEASURES ON THE WEST COAST OF THE SOUTH ISLAND

A THESIS

SUBMITTED FOR THE DEGREE

OF

DOCTOR OF PHILOSOPHY IN GEOLOGY

IN THE

UNIVERSITY OF CANTERBURY

BY

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UNIVERSITY OF CANTERBURY

1985

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ABSTRACT

An extensive study of Paparoa Coal Measures (Upper Cretaceous - Paleocene) and Brunner Coal Measures (Paleocene - Eocene) in 3 major West Coast coalfields has been undertaken, incorporating data from field exposures and drillholes, coal petrology, and interpretation of coal analyses.

Earlier paleogeographic interpretations for Paparoa Coal Measures at Greymouth Coalfield are amplified and links established with Pike River Coalfield, where Paparoa Coal Measures are described and inferred to represent more proximal sedimentation in a narrow fault-bounded basin common to both coalfields. It is proposed that syndepositional differential subsidence acted in both areas to localise major fluvial channels to zones of most rapid subsidence. The complex paleogeography caused by sedimentation in a tectonically active sedimentary basin was locally more favourable for accumulation of thick clean peat than would be expected if the basin had subsided uniformly.

Petrological studies demonstrate that, despite an overwhelming predominance of vitrinite, both Paparoa and Brunner coals exhibit significant variability in maceral characteristics and assemblages, which can be related principally to swamp drainage. Type variation is manifest not only by maceral characteristics but also by substantial variability in volatile matter yield *and vitrinite reflectance*, which exhibit a linear inverse relationship in isorank (equal thermal maturity) samples, attributed to variability in peat oxygenation.

Relationships between variability in (a) lithostratigraphic characteristics, such as member thickness, texture and composition, and abundance of coal, (b) seam thickness and coal quality, and (c) coal type, including any analytical property which varies as a consequence of type variation, are used in detailed paleogeographic and paleoenvironmental reconstruction, with emphasis on coal swamps and their interaction with adjacent sedimentary environments. The resulting models are proposed as a basis for seam correlation in situations where paleoenvironmental complexity causes rapid variations in seam thickness and quality. Several case studies including both intermontane Paparoa and marginal marine Brunner Coal Measures are demonstrated.

CHAPTER 1

GENERAL INTRODUCTION

1.1 HISTORY AND DESCRIPTION OF THE RESEARCH

The subject of this thesis is West Coast coal measure paleoenvironments, and their influence on seam characteristics and coal properties, particularly coal type. When research reported here commenced in 1978, paleoenvironmental investigations of New Zealand coal measures were rare and the petrology of New Zealand coals had received only cursory attention, almost entirely overseas. Indigenous petrographic study of coal macerals appears to have been restricted to Te Punga's reconnaissance evaluation of thin sections (Te Punga 1949). In view of overseas developments in coal studies and a local resurgence of interest in coal as an energy resource, an investigation of New Zealand coal measures appeared timely. Upper Cretaceous to Paleocene Paparoa Coal Measures (CM) at Greymouth Coalfield (Figs 1 & 2) were chosen initially as the primary subject of the work for several reasons. The stratigraphy and structure of Greymouth coal measures had already been described in detail (Gage 1952), providing a reliable foundation on which to base advanced work. Paparoa CM at Greymouth are thick, exhibit diverse sedimentary facies and complex stratigraphy, and well developed seams of low ash, low sulphur bituminous coal have been mined at several horizons. It was anticipated that a variety of paleoenvironments, and thus some diversity in seam characteristics such as geometry, mineral matter content, and coal type, would have resulted from the obviously complex depositional history of the coal measures. The fundamental aim of the research was to determine how paleoenvironmental factors influenced peat accumulation and eventual coal character, and an integrated study of coal measure sedimentology and coal type was perceived as the best means of achieving this aim.

At the time research commenced, two other Ph.D. studies were conceived on related topics. These were the sedimentology and coal petrology of the Eocene Brunner CM, and the mineral matter and inorganic geochemistry of West Coast coals. Geochemical research aimed to

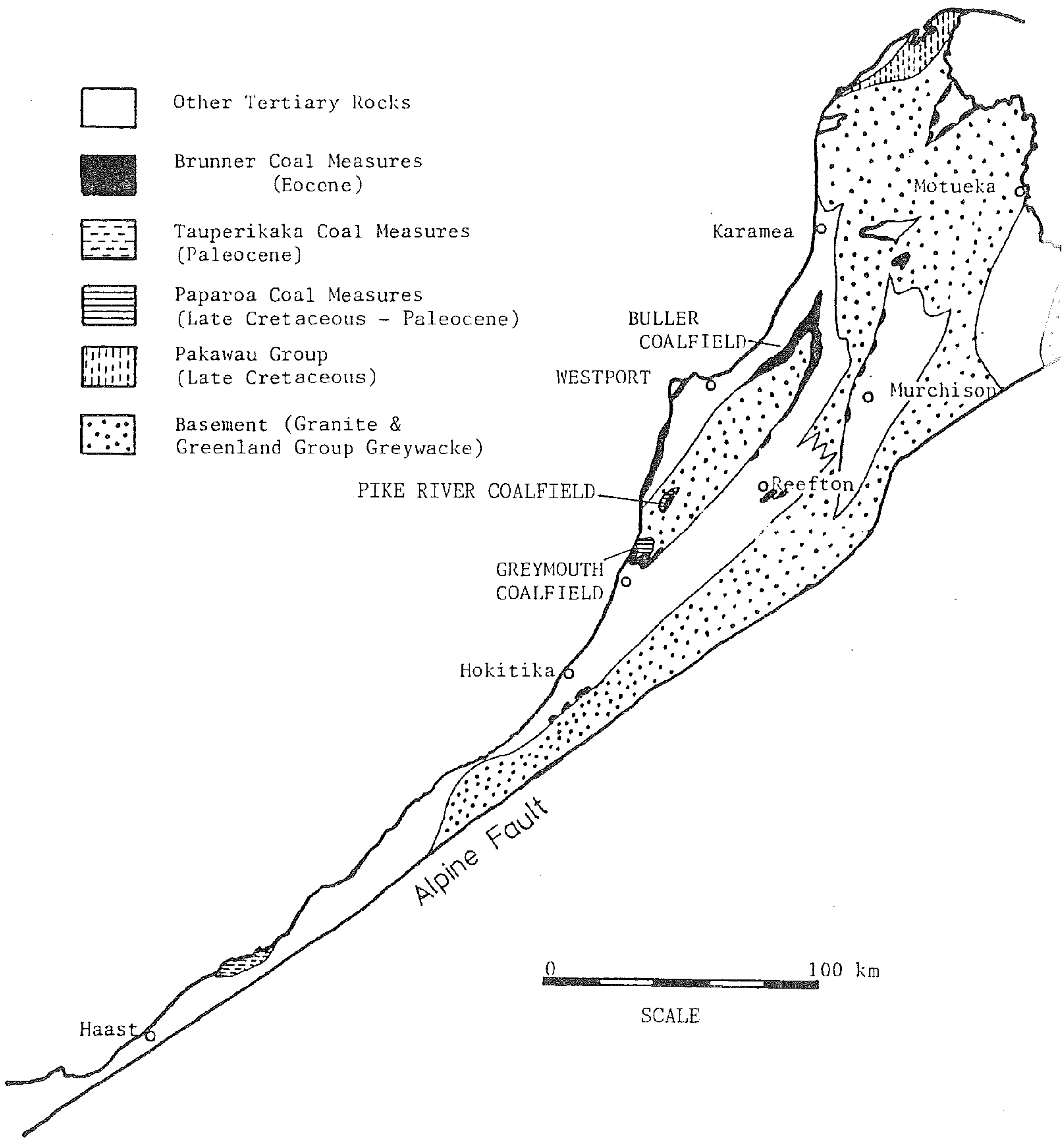


FIGURE 1. Location map showing West Coast coal measures of Cretaceous and lower Tertiary age.

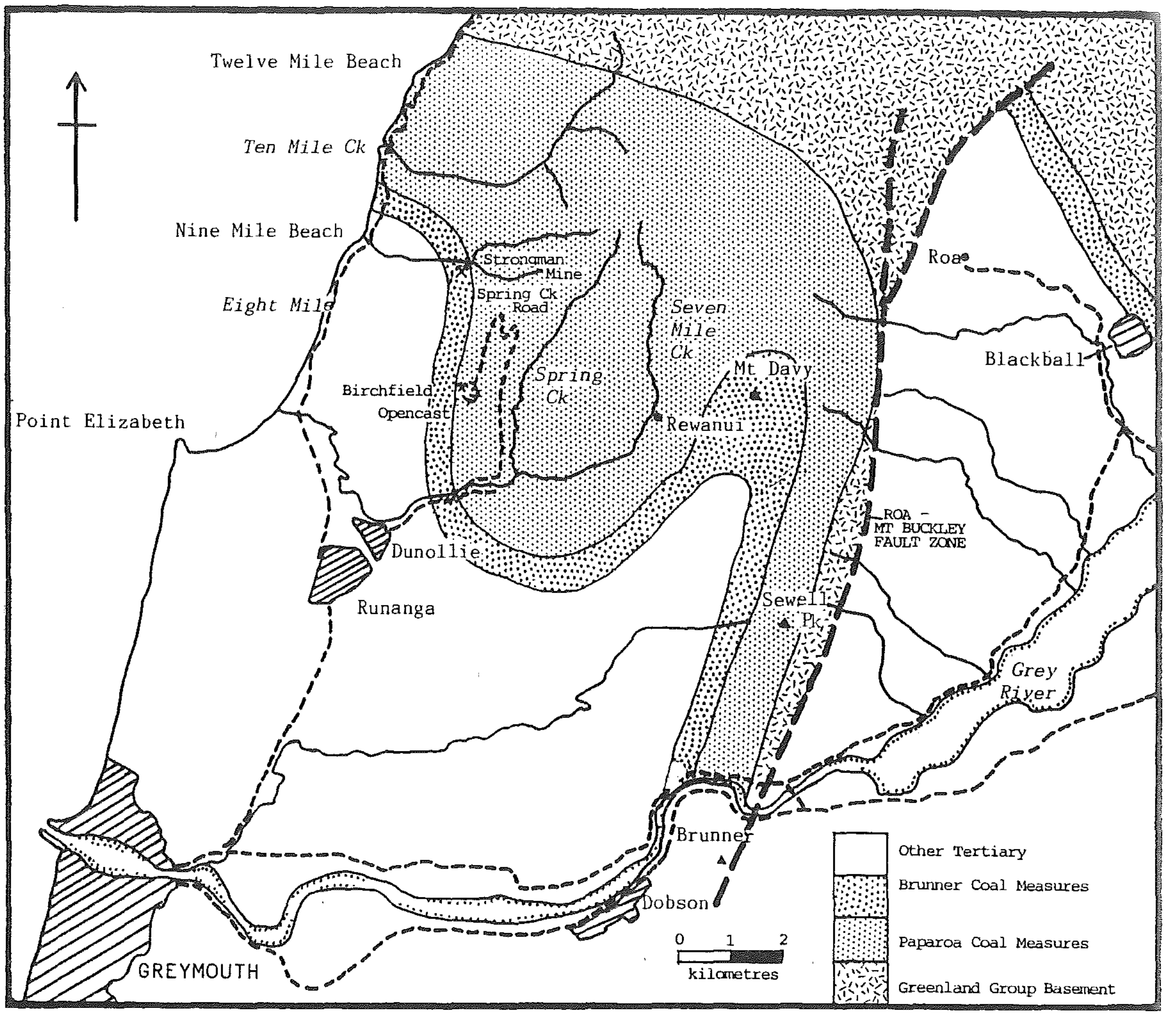


FIGURE 2. Map of Greymouth Coalfield showing localities cited in text, and simplified geology.

encompass both Paparoa and Brunner coals. Simultaneous research on all three Ph.D. topics was expected to augment individual findings with valuable comparative information, permitting a broader understanding of the way in which depositional controls influenced seam behaviour, coal type, and coal quality.

In the absence of New Zealand experience in coal petrology, considerable time was required at the onset of research to develop suitable methods of sample preparation and an understanding of the principles of coal petrology. New Zealand's bituminous coals are physically and petrologically distinct from most overseas bituminous coals and traditional techniques and concepts could not be applied without modification. In early 1978, several weeks were spent in the Geology Department of Wollongong University, Australia, learning the fundamentals of coal petrology under the supervision of Professor A. C. Cook. This was an important initiation, providing sufficient grounding for subsequent work to proceed without tuition. Air fares for this visit were met by a McKee Scholarship. Additional funding for the first four years of the Ph.D. was provided by University Grants Committee and BP (NZ) Ltd Postgraduate Scholarships.

During 1979 a revised model of Paparoa CM paleogeography was developed, based on field studies in remote parts of the Greymouth Coalfield (Newman, J. 1979). After the commencement of a long term reconnaissance drilling programme by Mines Division, this preliminary model was expanded and refined, including subsurface coal measures not previously explored. This resulted in a model relating coal measure sedimentation to patterns of basin subsidence (Newman, J. 1981). The programme also provided numerous coal samples and analyses which have been the subject of research from 1981. Another fortunate occurrence in 1979/80 was the commencement of exploration activity at Pike River Coalfield by Otter Minerals (now Pike River Coal Company). Although only the Brunner CM have so far been drilled in the course of this exploration, considerable mapping, sampling, and analysis of both Paparoa and Brunner coals has taken place. Close cooperation with the company throughout, with the writer in an advisory capacity, has greatly benefited research. In particular, studies of lateral changes in sedimentary facies at Pike River Coalfield (Newman, J. and Newman, N.A. 1981; Newman, J. 1982a) supported tectono-sedimentary models postulated for Greymouth, and the petrology of Pike River coals (Newman, J. 1982b&c) provided the first evidence for an important relationship between coal type and vitrinite reflectance in isometamorphic West Coast coals (Newman, J. & Newman, N.A. 1982).

Commencement of new exploration programmes provided unexpected opportunities to work on potentially important coal measures which were previously inaccessible. In order to reserve time for such work, I decided to limit most attention at Greymouth Coalfield to the Rewanui Member of the Paparoa CM, and to the overlying and underlying Goldlight and Waiomo Members with which the Rewanui is partly time equivalent. Consequently the older Jay, Ford and Morgan Members, and the Dunollie Member, have been largely neglected (but see Appendices 1 and 2).

From 1981 to 1984, research targets were specifically tailored to coordinate with the needs of Mines Division and Pike River Coal Company, to the mutual benefit of all parties (e.g., Newman, J. 1983).

During this period funding was provided by the New Zealand Energy Research and Development Committee. A consequence of sustained interaction with the industry was extension of research to include some Brunner CM, principally those at Pike River Coalfield but also to a lesser extent those at Buller (Newman, J. 1984a&b). Provision of drill-logs, samples, and coal analyses from substantial exploration programmes at all three major coalfields permitted thorough testing of initial hypotheses and establishment of important relationships between paleoenvironment and coal properties in both Paparoa and Brunner CM in a number of localities. The initial objectives of the research were in this way achieved and in some respects surpassed.

1.2 REGIONAL GEOLOGY

Almost all New Zealand bituminous coals occur on the West Coast of the South Island (Westland and Northwest Nelson; Nathan, <u>in press</u>), principally within the uppermost Cretaceous to lowermost Tertiary (Haumurian-Teurian) Paparoa Coal Measures (CM) and the lower Tertiary (mainly Eocene) Brunner CM (Fig. 1). The two successions are superimposed at Greymouth and Pike River Coalfields (Gage 1952; Wellman 1948; Nathan 1978; Laird <u>in press</u>), but elsewhere the Paparoa CM are absent and Brunner CM rest on middle Cretaceous terrestrial sediments or older granite and greywacke rocks. Laird (1968) postulated an extensional (rift) basin system for middle Cretaceous terrestrial sequences (Pororari Group), a tectonic model which is also pertinent to the Paparoa CM. Research documented in this thesis demonstrates that syndepositional, probably normal faulting, exerted an important influence on the highly variable paleogeography, sedimentary facies, and coal seam characteristics of the Paparoa CM.

Brunner CM are relatively widespread and thin compared with Paparoa CM, and generally exhibit less extreme lateral variability in stratigraphy and sedimentology. However, from coalfield to coalfield a range of depositional environments is represented. Whereas the Paparoa CM are entirely independent of marine influence, the Brunner CM accumulated in association with a widespread marine transgression, and a fluvial to marginal marine environment is indicated by sedimentology and coal type. Brunner CM are invariably overlain - often gradationally - by marine and marginal marine lithologies.

Regional subsidence, with sedimentation of marine sandstones, mudstones and limestones, prevailed for most of the Tertiary. Omotumotu and Kongahu Member mass flow deposits (Nathan 1978; German 1976) in both Eocene and Oligocene sequences suggest continuation of the syndepositional faulting which characterised Cretaceous basin development. Greatest Cretaceous-Tertiary subsidence occurred in a north-northeast trending trough (Paparoa Tectonic Zone, Laird 1968) which passes through what are now Greymouth, Pike River and Buller Coalfields.

This trough everted during the Kaikoura Orogeny (Late Miocene to Recent) to form the imposing Paparoa and Papahaua Ranges (Figs 3 & 4). An elevated (to >1000m) and often rugged physiography is consequently a feature of the principal coastal coalfields, and the highest rank coals (high volatile bituminous A to semi-anthracite) are typically found in high country. It is probable that coking coal originally occurred more or less continuously between Greymouth and Buller Coalfields, but erosion following uplift has left a substantial remnant only at Pike River. To the east and west, the Paparoa Tectonic Zone is flanked by relatively low rank Brunner CM (lignite to high volatile bituminous C), and similarly low rank Paparoa and Brunner coals occur beneath approximately 500m of Tertiary cover between Greymouth and Hokitika (Newman, J. et al. 1980). Due to their eventful tectonic history, most West Coast coal measures are faulted, some severely, and dips frequently exceed 15°.

1.3 HISTORICAL BACKGROUND

Coal was first discovered in the Greymouth area by Thomas Brunner in 1848 (Morgan 1911), along the banks of the Grey River at Brunner (Fig. 2). In company with Charles Heaphy, Brunner also made the first discovery of coal in the Westport area, when they found the Charleston lignite in 1846. However, bituminous coal was not discovered until John Rochfort and Julius von Haast located outcrops on the Denniston plateau in 1859 and 1860 (Morgan & Bartrum 1915). Coal mining commenced at Greymouth in 1864 and at about the same time at Buller, although ventures in the latter area appear to have been relatively unsuccessful for some years. Subsequent mining history in both coalfields has at times been eventful, with a strong political element (May 1975) and several mine disasters which at Greymouth have taken the lives of 100 men (Newman, J. et al. 1980). The earliest incident caused 66

deaths in a single explosion at the Brunner Mine in 1896.

In Westland, mining has been virtually limited to the c. 100 square km constituting Greymouth Coalfield. To date this area has produced approximately 30 m tonnes of coal from more than 100 mines, of which the largest have been State operations. Approximately 8 small private mines are currently active, and one large State mine (Strongman) which requires new development in the near future to remain viable. Geological conditions at Greymouth are generally unfavourable for opencast mining and limit underground ventures to traditional bord and pillar techniques. Reserves at Greymouth include both steaming and coking coals which have in the past been extensively utilised by transport, industrial, and domestic consumers. Current exploration for new reserves is aimed principally at the export market.

Pike River Coalfield lies above 750m elevation on the crest of the Paparoa Range inland from Punakaiki (Fig. 1) and has never been accessible by road. Thick coal was reported by early visitors to the area and the occurrence was documented by Morgan (1911) and Henderson (1917), although neither had visited the area. H J Wellman was the first geologist to reach the coalfield when he traversed from the Grey Valley to Punakaiki in 1946 and briefly examined the coal measures in the northern end of the field. The following year G W Patterson examined a section in the south (Wellman 1948). Development and mining has been prevented in the past by the isolation of the field.

Widespread substitution of cheap petroleum products for coal, and the burden of heavy Government subsidies to support many underground State mines, lead to closure of several large operations and a general decline in the coal industry in the 1960's and 1970's. However, interest quickly revived when oil prices increased in the 1970's, and major exploration programmes consequently have been initiated at Greymouth, Pike River and Buller Coalfields. The Mines Division Coal Resources Survey has resulted in approximately 50 holes being drilled at Greymouth since 1978, and a larger number at Buller since 1983. A private company (Pike River Coal Company) has undertaken extensive outcrop sampling and a 6 hole drilling programme at Pike River Coalfield since 1980.

1.4 PREVIOUS GEOLOGICAL WORK

A number of 19th century geologists and explorers documented aspects of the geology and early mining of West Coast coal measures. Notable among these workers were Haast, Hector, Hutton, Hochstetter, McKay, and Park. Their work was collated and extended by Morgan who researched and compiled Geological Survey bulletins on the Greymouth and Buller-Mokihinui Subdivisions (Morgan 1911; Morgan & Bartrum 1915). These were general works but coal was prominently featured in both volumes.

The geology of coal measures in the Buller region is simple, involving one principal formation, the Eocene Brunner CM, which rarely exceed 70m thickness and contain only one or two seams at any one locality. The coal measures are, broadly speaking, uniform in character, and well exposed in the high rank tablelands north of Westport. Morgan and Bartrum (1915) were consequently able to provide good coverage of the most important sector of the coalfield, delineating seam outcrops and major structural elements.

In contrast, coal measures at Greymouth are stratigraphically, sedimentologically and structurally complex, particularly in the case of the Paparoa CM. Exposure is poor due to heavy bush cover and the terrain is more rugged and inaccessible than the plateau areas at Buller. Consequently, Morgan (1911) settled for a relatively superficial coverage of the geology, documenting some important coal outcrops and faults and delineating the contact between Brunner and Paparoa CM. He recognised that the Paparoa CM comprise three rhythms of sandstone and shale, but did not attempt to map these out as separate formations.

Between the 1st and 2nd World Wars, studies were conducted locally by Mines Department and Greymouth Harbour Board personnel, but detailed geological reappraisal on a regional scale was delayed until the Geological Survey undertook the task during World War II. Aerial photographs were not at first available and extensive surveying was an essential adjunct to geological mapping. Among the geologists was Maxwell Gage, who eventually took charge of the work and published it as N.Z. Geological Survey Bulletin 45 (Gage 1952). This bulletin included a comprehensive chapter on coal rank and type by Wellman, who recognised that the lower+middle Paparoa, upper Paparoa, and Brunner coals formed three distinct types on the basis of chemical analyses.

Gage (1952) subdivided the Paparoa CM into seven formations of alternating fluvial and lacustrine character, and recognised that lateral changes in thickness and lithofacies produced a very complex stratigraphy. Extremely thorough mapping of the coalfield, with data from several deep drillholes and working mines, resulted in very detailed geological maps at a scale of 1 inch = 0.25 miles, on which each formation was mapped individually. Work at this scale provided considerable structural information and details of seam distribution, of particular relevance to coal exploration and mine development.

In addition to describing stratigraphy and structure Gage discussed coal measure lithologies and considered the probable depositional setting of the Paparoa CM in particular. He envisaged the basin as a northeast trending, rapidly subsiding trough with a western source area and a history of lacustrine transgression and regression. He considered that the coals accumulated in lake-fringing swamps. Gage's major interpretations remain substantially valid today.

Numerous papers and reports on coalfield stratigraphy and reserves appeared after Bulletin 45, some as a consequence of new drillholes (e.g. Suggate 1955). From 1947 to 1959 a substantial quantity of this work was by Suggate, who used considerable information on West Coast coals in his important Bulletin 134 on the properties of New Zealand coals (Suggate 1959). This Bulletin presented a revised and extended version of Wellman's coal type and rank theories.

Nathan (1978) published a 1:63,360 scale geological map of the Greymouth District. While he expanded previous work on Tertiary marine lithologies, Nathan essentially reproduced Gage's mapping of the coal measures without significant amendment. However, he revised the stratigraphic nomenclature. Whereas Gage regarded the seven Paparoa CM subdivisions as formations, Nathan redesignated them members, reasoning that they could only be recognised within the Greymouth area and several pinch-out locally. Although it is now possible to tentatively correlate distinctive Paparoa CM units between Greymouth and Pike River Coalfields on a lithological basis, there is unfortunately no paleobotanical substantiation of these correlations. Nathan's nomenclature is now generally used by coal industry personnel, and is adopted in this thesis.

Recent geological work in Greymouth includes reports on specific coalfield localities by D. F. Thorburn, who was Mines Division district geologist from 1979 to 1981. His report (Thorburn 1981) on coal measures in the Strongman Mine area has assisted part of the writer's research.

Until recently, all previous work at Pike River Coalfield was limited to Wellman's paper (1948), which provided a very simple but largely accurate geological map (1cm = 1km) and some lithostratigraphic data. A single thick and extensive coal seam was identified as part of the Brunner CM and four Paparoa coal seams were recorded in a section at the south of the field. Wellman recognised lithological similarities between middle and upper Paparoa beds at Pike River and middle and upper Paparoa sequences at Greymouth. In the 1960's, Pike River Coalfield was visited by Laird in the course of regional mapping for the Punakaiki 1:63,360 geological map (Laird, in press). Laird focussed on the Middle Cretaceous Pororari Group, and Upper Cretaceous coal measures were little studied. However, his work served to accurately delineate the base of the coal measures and located a thick lower Paparoa seam in the centre of the field. In the early 1970's Robertson Research (Australia) Ltd undertook reconnaissance field mapping and sampled coal at thirteen sites. Their work was handicapped by bad weather and coverage of the field was consequently very limited. Analytical and petrological work on the samples produced confusing data which were wrongly interpreted, resulting in erroneous conclusions regarding geological history and coal rank variation (Allen et al. 1974). Recent work on Pike River Coalfield has been undertaken by Pike River Coal Company (Bates 1981) and myself.

CHAPTER 2

COAL MEASURE CHRONOLOGY, WESTLAND

2.1 GREYMOUTH COALFIELD

2.1.1 Introduction to Stratigraphy

Paparoa CM at Greymouth are characterised by rapid lateral variations in thickness, and by lateral and vertical changes in lithofacies in many areas. Some members have a very complex three dimensional configuration because of lateral facies changes and thinning over irregularities in the basin floor. Gage envisioned accumulation of lower Paparoa CM (Fig. 5), i.e. Jay and Ford Members,

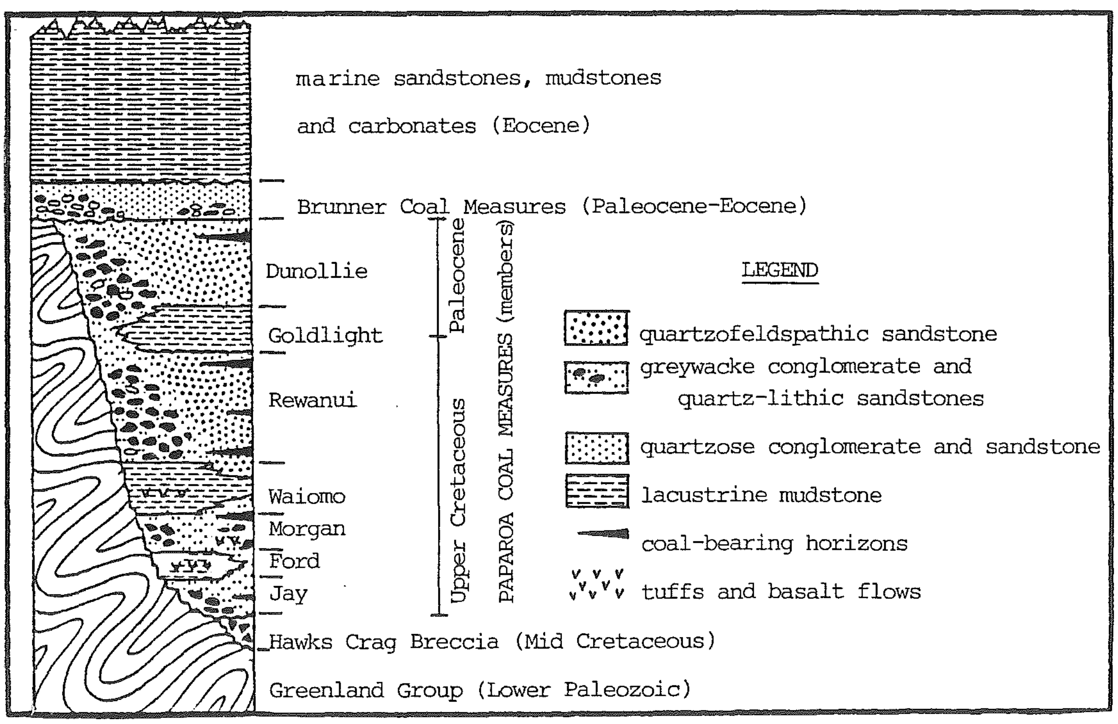


FIGURE 5. Diagrammatic stratigraphic column for Greymouth Coalfield, not to scale.

in several small sub-parallel troughs trending west-northwest. Conversely, he considered younger coal measures (Waiomo to Dunollie Members) to have accumulated in a single relatively large trough trending north-northeast and superimposed on the earlier deposits.

The intervening Morgan Member was recognised as a complex unit which appeared to exhibit elements of both earlier and later depositional trends. Although recent exploratory drilling has shown that Gage's extrapolations into subsurface areas in the south and west are only partly correct, his general concept of contrasting lower and upper Paparoa basin trends appears valid. Morgan, Rewanui and Dunollie Members are conglomeratic in the west, indicating a local source area now to seaward.

2.1.2 Chronology

(a) Previous work. Paparoa and Brunner CM ages at Greymouth Coalfield were until recently the subject of speculation, due to inadequate paleobotanical control. Morgan (1911) favoured an Eocene age for both sets of coal measures. Gage (1952) considered the Paparoa CM to be Upper Cretaceous, and the Brunner CM in the range Upper Cretaceous to Eocene. When Nathan's (1978) one mile sheet was published, palynological data were interpreted by the Geological Survey to indicate a Raukumara to Mata (Mid to Upper Cretaceous) age for the Paparoa CM. The age of the Brunner CM in the Coalfield area was still uncertain, but appeared likely to be Eocene on available evidence. Subsequent work by the Geological Survey redefined the Paparoa CM as Haumurian-Teurian, with the Cretaceous-Tertiary boundary located within the Goldlight Member (Raine 1981). The Brunner CM were not reinvestigated. My research has revealed an unusually complex Brunner CM chronology, as discussed in the following section.

(b) Revision of Brunner Coal Measure Chronology

(i) Previous work. Brunner CM at Greymouth were defined by Gage (1952, p42) as "the lithologically distinctive quartz conglomerate, leached greywacke conglomerate, quartz sands, and carbonaceous shales that .... contain a high-volatile, high-sulphur type of coal". Wellman (1950), Nathan (1978), and the writer prefer to relegate the leached greywacke conglomerates, which occur at Nine and Ten Mile, to the upper Dunollie Member on the basis that they appear to have been weathered *after* sedimentation, and are clearly unconformably overlain by quartzose Brunner conglomerate.

Although the bulk of the Brunner CM are not difficult to identify and differentiate from Paparoa CM on a lithological basis, the chronological relationships of the two sets of coal measures and the overlying middle Eocene Island Sandstone were until recently the subject of speculation. Gage (1952) postulated that the quartzose coal measures occurring at the base of the Tertiary marine succession in widely separated parts of the South Island were likely to have resulted from a single widespread peneplanation and hence share a common, probably Upper Cretaceous, age. However Suggate (1949) regarded most quartzose coal measures as an early product of marine transgression, and consequently similar in age to overlying marine sediments, which were known to be Bortonian (middle Eocene) in Greymouth. Gage pointed out that both theories might be correct because even thin quartzose coal measures could represent a very long period of time; in other words he implied that the Brunner CM could span Upper Cretaceous to Eocene time. Suggate also conceded that in some circumstances quartzose coal measures could span several stages without significant unconformity, i.e., in cases where gradual accumulation occurred in small repositories whilst surrounding areas underwent peneplanation. He suggested that this mode of accumulation, which conforms with Gage's model, could pass conformably into the more widespread variety associated with marine transgression.

Couper (1960) examined three Brunner CM samples from Greymouth (Eight Mile, Nine Mile, and Blackball localities, Fig. 2) and assigned all of them to the Bortonian Stage (Middle Eocene age) on palynological grounds; as Nathan (1978) pointed out, coal measures in the centre of the coalfield remained undated. In the centre of the coalfield the uppermost Dunollie frequently consists of a thin (0 - 30m) sequence of greywacke conglomerate, which at a number of localities becomes increasingly quartzose upwards. The transition from Paparoa to Brunner CM at Sewell Peak is described by Nathan (1978, p13) as follows:

> The base of the Brunner Coal Measures is marked by a rapid but gradational change to quartz conglomerate, and the overlying beds consist mainly of quartz conglomerate and sandstone. Although the base of the Brunner Coal Measures is marked by an increase in the proportion of quartzose sediments there is no sign here of any weathering of the underlying beds nor of an erosional break, and the upper part of the Dunollie Coal Measure Member is significantly more quartzose than underlying parts of the Paparoa Coal Measures. .... It is inferred that although there was no sedimentation over most of the West Coast in pre-Brunner time, it continued locally along the axis of the Paparoa Geosyncline.

Nathan therefore implied that the Brunner CM must span the entire period separating Paparoa CM and Island Sandstone accumulation (Teurian-Bortonian, c.8myr).

(ii) Current work. The stratigraphy of Brunner CM at Greymouth first affected current research during reconnaissance investigation of a well exposed Dunollie Member - Brunner CM sequence at Spring Creek Road (Fig. 2). A 4m thick coal seam occurs at the Brunner CM - Island Sandstone contact at this locality, and a small opencast mine ("Birchfield's") operated for several years until 1982. Attempts to identify a clear lithostratigraphic contact between Dunollie sediments and Brunner CM in the course of section description were frustrated by the same gradational characteristics described by Nathan (1978) at Sewell Peak. The contact between the coal seam and overlying Island Sandstone also appeared conformable, as indicated by intercalation of coal and sandstone at the roof and the occurrence of a 10cm "rider" seam in Island Sandstone 2m above the main seam. A series of samples was collected for palynological dating in the hope that they would resolve the stratigraphic relationships (Fig. 6). These samples were examined by J. I. Raine of the NZ Geological Survey, who determined that Brunner CM at Spring Creek Road are palynological Zone D (Teurian - ?Waipawan Stages, Paleocene - ?lowermost Eocene), hence inseparable in age from the underlying Dunollie Member (Raine 1980 pers. comm.; Newman, J. et al 1980). During subsequent work on the samples (Raine 1982), the coal seam itself was found to contain flora suggestive of ages ranging from Zone B - ?Zone C (possibly transitional, i.e., Teurian - Waipawan) at the base, to "a conifer-rich type of Zone C, or maybe late Zone B" (hence anything from Teurian to lower Bortonian) 0.5m from the top of the seam, to "Zone C" (Waipawan to lower Bortonian) at the top (Fig. 6). The thin "rider" was assigned to Zone D. Preservation of flora within the seam is poor, and Raine (pers.comm.) is as yet uncertain of the precise zonation. Detailed palynological descriptions of the samples appear in Appendix 3. In summary, palynological data suggest that the 4m seam at Spring Creek Road may span most of Zone C, estimated by Raine to encompass c. 8 m yr. Peat may not have accumulated continuously during this time, but the existence of an extremely long-lived swamp, undisturbed by clastic sedimentation, is indicated. There is no evidence of unconformity at any point in the succession. Limited petrographic work on the Brunner seam at Birchfield's indicates that the coal macerals are frequently severely degraded and may well represent very slow peat accumulation. In general

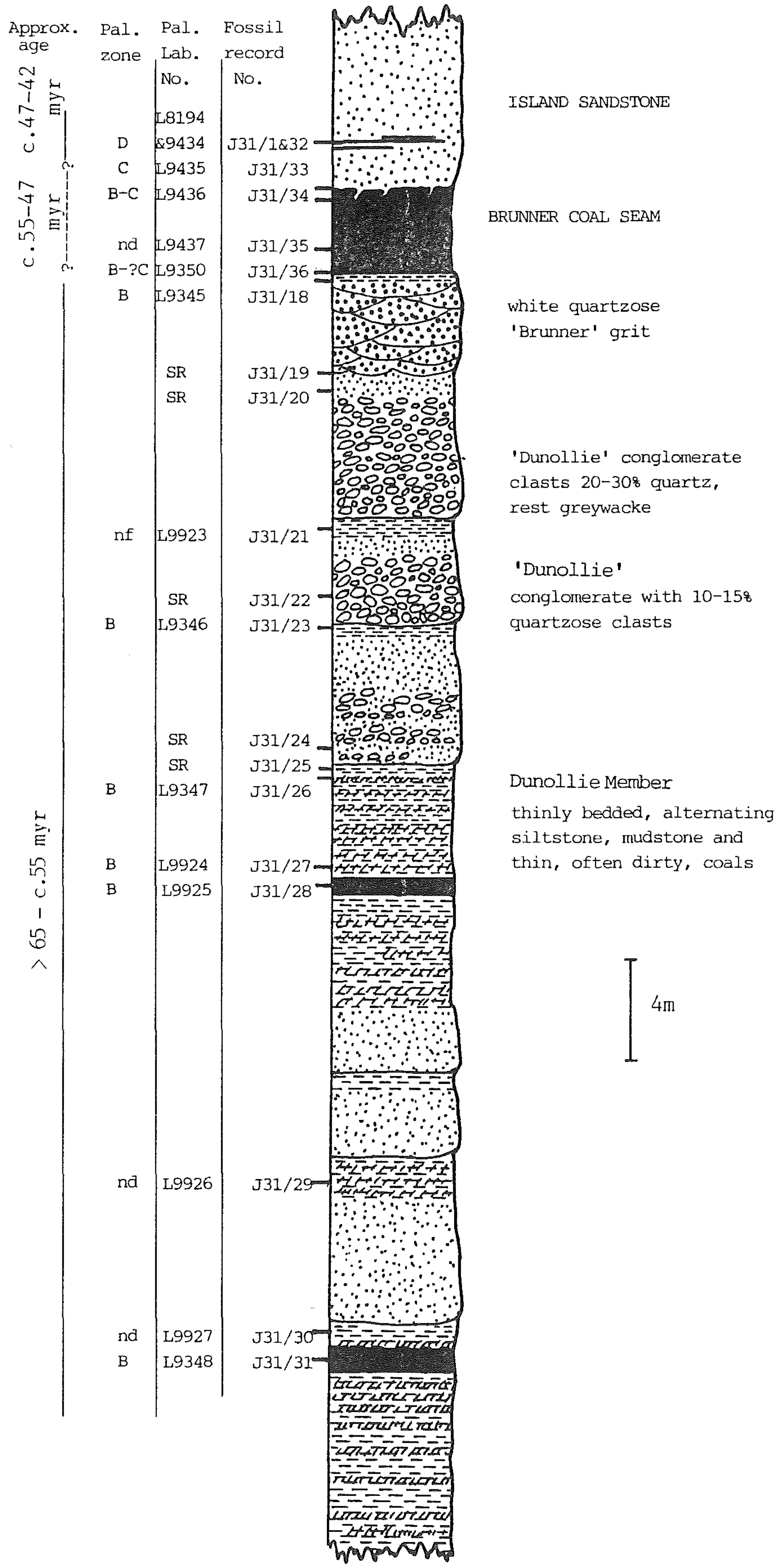


FIGURE 6. Stratigraphic column of the section from Birchfield's Opencast eastward down the hillside towards Spring Creek Road, Greymouth, showing the lithologies and pollen dates for the uppermost Dunollie to Island Sandstone sequence. Palynology by J. I. Raine, New Zealand Geological Survey.

terms the coal resembles Brunner coals at Pike River Coalfield (see 4.5).

Resolution of biostratigraphy at Spring Creek prompted investigation of the Sewell Peak Section, where Brunner CM are thicker and more varied in lithology. The Brunner CM - Dunollie Member contact is gradational, as discussed by Nathan, and the transition from upper Brunner CM (containing a 1m seam) to Island Sandstone is very gradual (Fig. 7). There is, however, an abrupt change in lithology <u>within</u> the Brunner CM. Cross-bedded granular quartz sandstones constituting the lower Brunner CM terminate upwards at a burrowed and highly silicified horizon, which is extensively exposed on dip slopes due to an absence of vegetation. Coal measures overlying this succession consist of much finer, parallel-laminated sandstones with abundant interbedded mudstone. These sandstones resemble Island Sandstone and some contain glauconite (D. W. Lewis, pers.comm.), but are generally regarded as Brunner CM due to the presence of coal. It seemed likely that the lower coal measures, which closely resemble the Brunner CM at Spring Creek, were Teurian and the upper coal measures Bortonian, in common with the Island Sandstone. The silicified horizon was considered to reflect an unconformity spanning the intervening c. 10 m yr. Although coal ranks are high in this area and palynological dating therefore not as promising as at Spring Creek Road, a series of samples was collected from the Dunollie Member up to the approximate base of the Island Sandstone (Fig. 7). These samples were examined by Raine, whose conclusions confirmed this hypothetical chronology (Raine 1982; Appendix 3).

(iii) Interpretation. The quartzose coarse sandstone lithofacies of the Brunner CM, which is dated as Teurian at Spring Creek and Sewell Peak, is thought to have accumulated during a period of slow subsidence in an area restricted to the centre of the trough in which Paparoa CM previously accumulated. The remainder of the old trough and areas beyond its margins became a quiescent, very low-lying source of quartzose residuum, generation of which may well have commenced in outlying regions some millions of years previously whilst Dunollie sediments were accumulating. Although the conglomerates which occur beneath the quartzose coal measures are traditionally assigned to the Dunollie Member, they may, in terms of tectonic history, be better regarded in association with the overlying quartzose sediments as a further

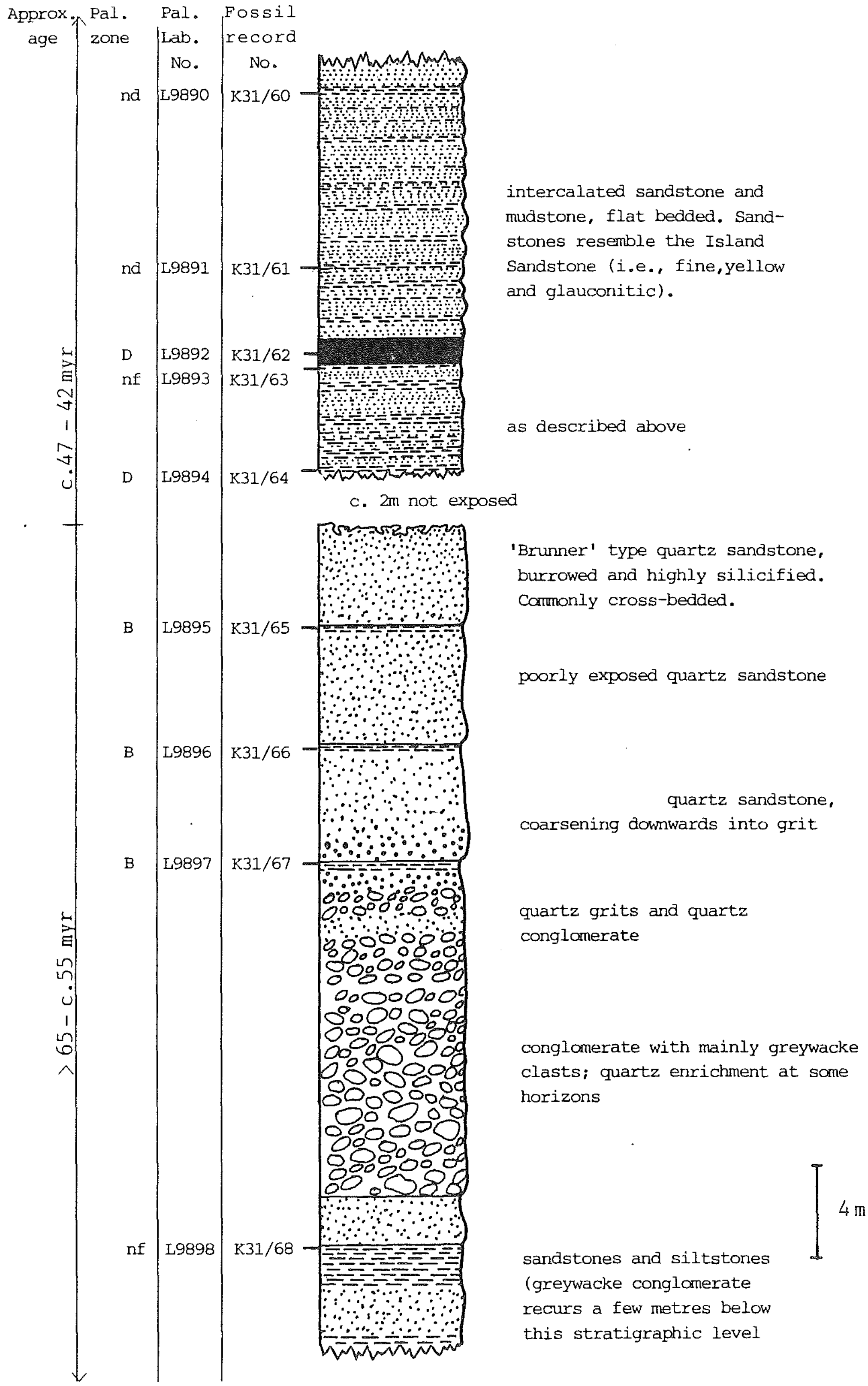


FIGURE 7. Stratigraphic column of the road and hillside section near the Sewell Peak Post Office tower, Greymouth, showing the lithologies and pollen dates for the Island Sandstone, Brunner Coal Measures, and the sediments which are documented (Gage 1952) as the conglomeratic uppermost unit of the Dunollie Member, Paparoa Coal Measures. Palynology by J. I. Raine, New Zealand Geological Survey.

cycle in the series previously exemplified by the Jay - Ford, Morgan - Waiomo, and Rewanui - Goldlight + Dunollie (see 3.2.1(d)) couplets. In this context, the apparently long-lived coal seam at Spring Creek, and the silicified unconformity at Sewell Peak, are the natural conclusion of diminishing rates of subsidence at the end of an upper Paleocene tectonic event. In contrast with earlier cycles, this latest one was initiated by relatively localised uplift and minimal subsidence as demonstrated by the laterally discontinuous and relatively thin (c. 30m) conglomeratic facies.

After a long period of tectonic stability during the late Paleocene and early Eocene, during which little sedimentation of any kind occurred on the West Coast, subsidence recommenced in the middle Eocene. This was a regional event, not limited to areas in which Paparoa CM and Paleocene-age Brunner CM are preserved. However, it seems probable that the original Greymouth basin still subsided faster than peripheral areas, because sedimentation within the trough recommenced in a marginal marine environmental setting (Island Sandstone at Spring Creek and coal measures with Island Sandstone affinities at Sewell Peak) while coal seams and terrestrial coal measures accumulated elsewhere, e.g., at Blackball, where the seam is known to be Bortonian (Couper 1960). Unfortunately, the age of important Brunner seams mined south of Sewell Peak at Brunner and Dobson is unknown, and possibly will remain so now that the mines are closed. Limited amounts of coal measure core available from early drillholes in this southern area might provide sufficient material for palynological dating.

In conclusion, recent work described above clarifies the history of Brunner CM accumulation at Greymouth, confirming and extending both Gage's and Suggate's tentative postulations regarding the setting and relative timing of depositional events.

2.2 PIKE RIVER COALFIELD

2.2.1 Introduction to stratigraphy

Paparoa CM at Pike River Coalfield range in thickness from c. 150 to 280m, and have been subdivided into 6 lithologically distinct members (Fig. 8). All members exhibit lateral faces changes and some

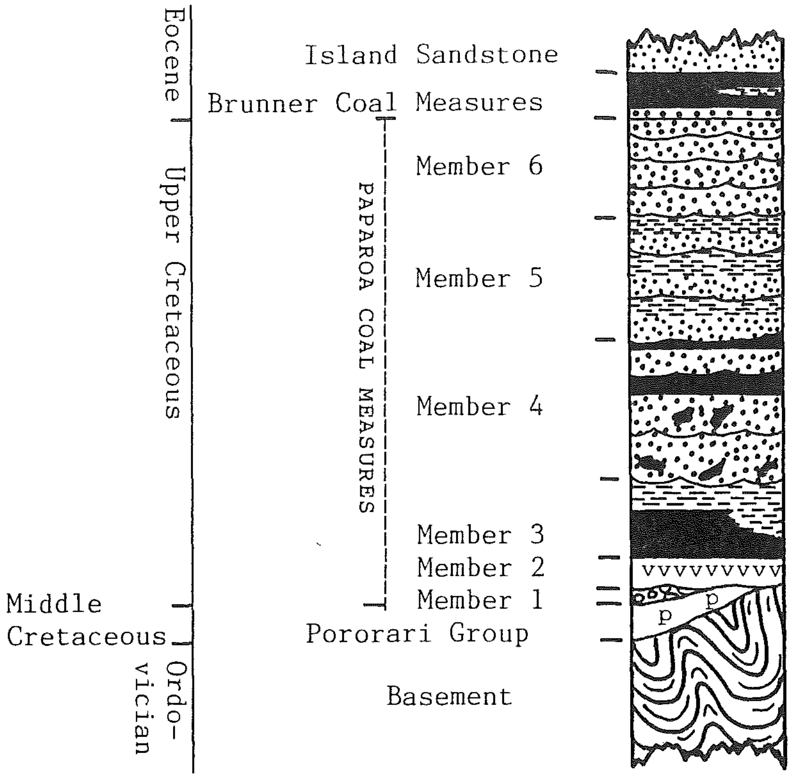


FIGURE 8. Diagrammatic stratigraphic column for Pike River Coalfield. Not to scale.

are locally absent; each is considered to represent a distinct depositional event. Brunner CM are limited in most exposures to a few metres of quartzose sediments and an overlying seam which generally exceeds 8m in thickness. Recent drilling in unexposed areas has demonstrated thinning and splitting of the seam about a mudstone parting (see 3.4.1).

2.2.2 Chronology

(a) Paparoa Coal Measures. Paparoa Members 3 (Fossil Record Numbers [FR No.s] K30/f11, K31/f58, 4 (FR No.s K31/53, 54 & 57), and 5 (FR No.s K30/4 & 5), have been palynologically assigned to the Haumurian Stage (uppermost Cretaceous, Fig. 9). Member 2 (M2) intercalates with basal M3 sediments, hence is also assigned to the Haumurian. M1 has not been dated. M6 yields poorly preserved pollen which indicate a Haumurian to Teurian Stage (FR No.s K31/52, K30/8832, Fig. 9).

(b) Brunner Coal Measures. Exposed Brunner CM have not been dated except in the far south, where Brunner coal is limited to 2 thin seams interbedded with sandstone (3.4.1). The upper seam has been dated as middle to upper Eocene (FR No. K31/6701, Fig. 9). Samples

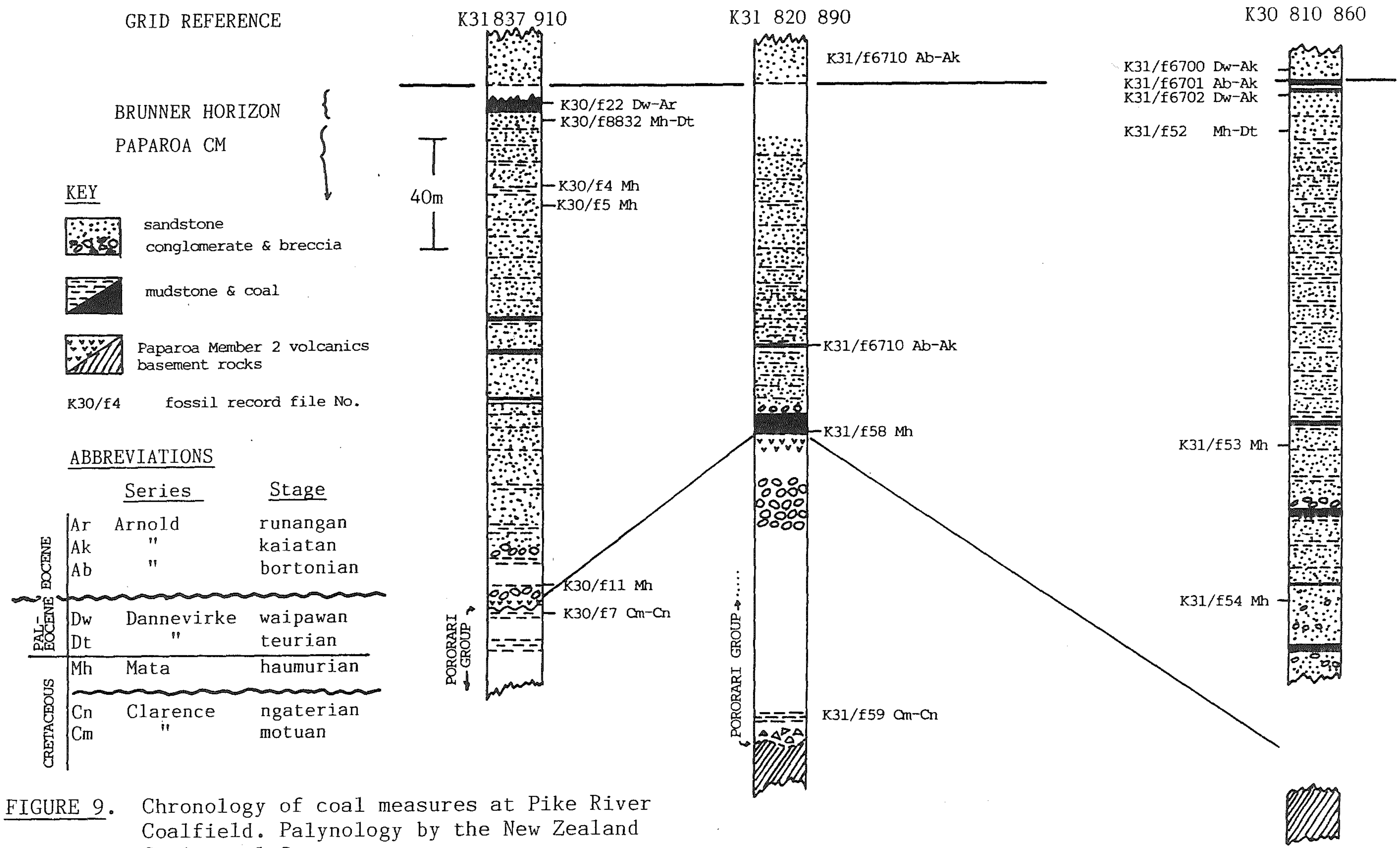


FIGURE 9. Chronology of coal measures at Pike River Coalfield. Palynology by the New Zealand Geological Survey.

from the recent drilling programme also indicate a mid to upper Eocene age (Fig. 10; Raine 1984).

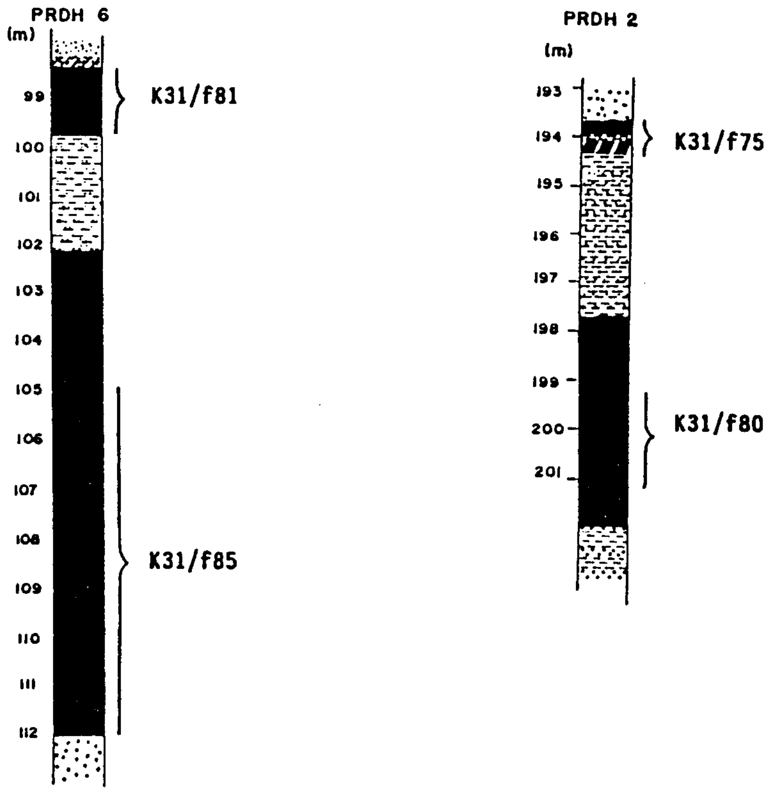


FIGURE 10. Samples used by Raine (1984) for palynological dating of Brunner Coal Measures at Pike River Coalfield. Poorly preserved pollen assemblages suggest a mid to late Eocene age (?Porangan - Kaiatan). For drillhole locations see Section 4.5.

2.3 CORRELATIONS BETWEEN PIKE RIVER AND GREYMOUTH COALFIELDS

2.3.1 Paparoa Coal Measures.

Paparoa Members 2 to 5 at Pike River Coalfield are Haumurian, in common with the Jay to Goldlight Members at Greymouth; current palynological zonation cannot subdivide the sequences further. Tentative correlations can be based on lithological similarity (Fig. 11). If the undated conglomerates of M1 are Haumurian they could correspond to either or all of the Jay, Ford and Morgan Members at Greymouth. M2 volcanics include basalts and appear likely to result from the same volcanic episode which is represented by basalt flows and breccias in the Morgan Member at Greymouth.

Quartzofeldspathic Rewanui to Dunollie sediments at Greymouth were derived from a northern source, probably north of Pike River Coalfield (see 3.2.2(g)), and Paparoa CM at Pike River and Greymouth Coalfields are considered likely to have accumulated in a common rift system. Sharing of a mutual source area and sedimentary basin can be expected to result in related histories of coal measure accumulation at the two locations, particularly in the case of sedimentation events which were controlled by episodes of source area uplift. Changes in rate of basin subsidence may also have been common to both areas. M3 mudstone accumulation at Pike River Coalfield was terminated by a high energy fluvial incursion which resulted in thick-bedded conglomeratic granular sandstones of M4. Similar events resulted in termination of Waiomo Member mudstone accumulation by Rewanui Member conglomeratic granular sandstones at Greymouth, hence tentative correlation is made between these Members and Pike River Paparoa Members 3 and 4 respectively (Fig. 11).

A fining-upward trend from M4 to M5 at Pike River represents declining current energy, possibly resulting from a rising base level (see 3.3.7). As Pike River Coalfield is inferred to have been situated up-paleoslope from Greymouth Coalfield in the same rift system, I infer that M5 accumulated contemporaneously with the Goldlight Member on a low-lying fluvial plain north of the "Goldlight" lake which developed

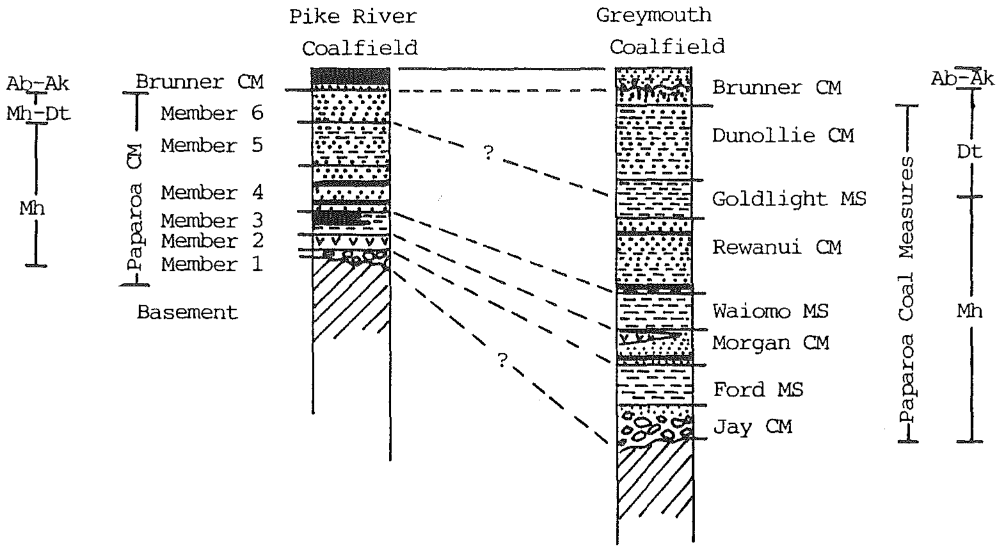


FIGURE 11. Suggested correlations between coal measures at Pike River and Greymouth Coalfields, based on lithostratigraphy and available pollen ages. Not to scale.

at and north of Greymouth. Compared with earlier members, M6 is more quartzose and uniformly bedded, and appears to represent fluvial sedimentation at a time of relatively slow subsidence, all characters shared by Dunollie sediments in Greymouth. These members are therefore considered likely correlatives (Fig. 11).

2.3.2 Brunner Coal Measures.

There are striking lithostratigraphic and coal type similarities between the Brunner CM sequence exposed in the Pike River escarpment and the sequence at Birchfield's Opencast, Greymouth (Fig. 6). However at Birchfield's Opencast, the coal measures are known to be Paleocene to basal Eocene (Raine 1982), whereas poorly preserved pollen assemblages from Pike River Coalfield drillhole samples indicate a mid to late Eocene age (Fig. 10), in common with the overlying marine Island Sandstone (Raine 1984). If the latter dates are reliable, Brunner CM at Pike River Coalfield correlate with the younger of the 2 sets of Brunner CM which occur at Greymouth. Alternatively, if the dates are not reliable the main seam at Pike River Coalfield may represent a condensed sequence deposited at a time of tectonic stability and subdued sediment supply. In this case the seam may rest more or less conformably on Teurian Paparoa M6, spanning the upper Paleocene to middle Eocene in common with the similar seam at Birchfield's.

CHAPTER 3

PALEOENVIRONMENTAL AND TECTONIC MODELS

3.1 GENERAL INTRODUCTION

As described in previous sections, many coal measure units in North Westland are highly variable in lithology and thickness and these variations are often abrupt. A major research objective was to analyse lithostratigraphic complexities, detect significant patterns, and determine fundamental controls. The scope of this aspect of the work was potentially very large, given that coal measures at Greymouth alone consist of eight distinct units spanning a vertical thickness up to 800m+ and an area of 100 square km. The unexpected commencement of a major (40 hole) drilling programme at Greymouth and exploration at Pike River Coalfield added sedimentological data not anticipated when the research programme was defined. In order to leave time for coal petrology, which was intended to constitute a substantial proportion of the work, I decided to avoid time consuming aspects of sedimentological study normally included in paleoenvironmental analysis. For example, detailed documentation of sedimentary structures and motifs or cycles, and intensive sedimentary petrography have been neglected in favour of a relatively broad-brush approach to basin analysis. Regional patterns of basin development and paleogeography are emphasised; recent drillholes are the principal source of data utilised for Greymouth Coalfield. Models which resulted from this first phase of investigation were later refined during more detailed studies of relatively small areas and restricted stratigraphic intervals. This second phase of work successfully combined simple lithostratigraphic analysis with coal type research, and is documented as a series of case studies in Chapter 4.

3.2 PAPAROA COAL MEASURE BASIN DEVELOPMENT AT GREYMOUTH

3.2.1 General description of members

(a) Jay, Ford & Morgan Members. Detailed information on these lower Paparoa members is largely restricted to Gage (1952). In contrast to the Rewanui Member, the Jay Member contains no known mineable coal reserves, and the once important Morgan Member no longer supports any mines, although some potential reserves may remain. All three lower members outcrop mainly in rugged and heavily bushed areas without road or rail access, and have been intersected by few drillholes during the current exploration programme.

Sandstones and conglomerates in the Jay, Ford and Morgan Members contain predominantly quartz and greywacke (highly indurated lithic sandstone and shale) clasts, and appear to consistently lack alkali feldspar and granite rock fragments (except in the west, where the Morgan Member has a minor acid volcanic source). This composition represents derivation from local Greenland Group greywacke basement, which lacks alkali feldspar (Nathan 1978). The older Paparoa sediments are thus compositionally distinct from the Rewanui and Dunollie Members, which are largely quartzofeldspathic and have a granitic source. Gage (1952) also made this observation.

Gage did not separate Paparoa CM from older sediments, although he acknowledged that the breccias constituting his lowest Jay interval ('Jay iii') probably correlated with Hawkes Crag Breccia which occurs elsewhere on the West Coast, and is now known to be middle Cretaceous in age. Nathan (1978) excluded this Jay iii interval from the revised Jay Member. Jay and Ford Members are both highly variable in thickness, laterally discontinuous (Gage 1952), and notably absent in the west. The Morgan Member rests on basement in the west and southwest and wedges out further to the southwest and south. The Member is usually c. 50m thick and workable coal seams occur locally near the upper and lower transitions to mudstone. A mixed basaltic and greywacke breccia-conglomerate facies occurs locally in the east where the Morgan Member is unusually thick (Gage 1952). A pyroclastic lens within the Member is known from recent Drillholes 631 and 632 in the Spring Creek area (Figs 2 and 12). Tonsteins (horizons of kaolinite lapilli) and mass flow deposits, both of volcanic origin (Newman, N.A. 1980), have been found by the writer in the Morgan Member at Twelve Mile Beach

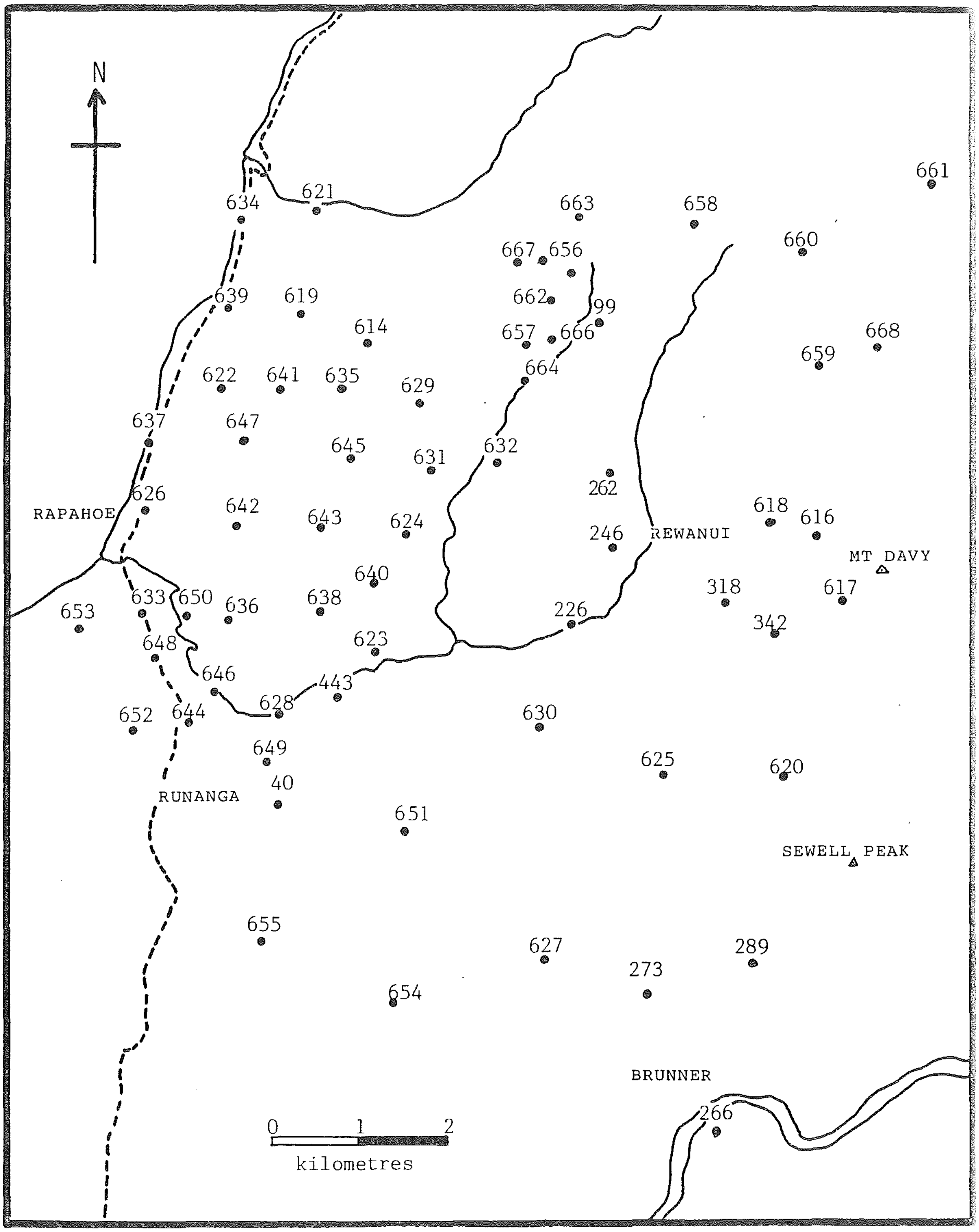


FIGURE 12. Location of principal Greymouth drillholes referred to in this thesis.

(Appendix 1).

(b) Waiomo Member. The Waiomo Member varies in thickness, usually between 50 and 100m, and becomes sandy towards the margins of the coalfield. The Member is extensive but pinches out in the south and southwest, where careful consideration of Waiomo and Rewanui thickness variations suggests that up to 50m of quartz-lithic sandstones at the base of the Rewanui are laterally equivalent to basinward lacustrine mudstones, hence may represent a lake margin facies of the Waiomo (see 3.2.2(b)). Thin pyroclastic beds are common in drill-core and exposures on the western side of the field, and geochemical analysis indicates a relatively acidic composition compared with the Morgan volcanics (N. A. Newman, pers.comm.). The Waiomo Member is chiefly of interest because it appears to be in part contemporaneous with the Rewanui Member, and the transition from lacustrine Waiomo to fluvial Rewanui deposition was associated with important peat accumulation in some areas.

(c) Rewanui Member. This important coal bearing member is thicker overall (up to 300m), and more extensive, than underlying members. Rewanui sediments overlap the Waiomo Member onto basement in the southwest and south, thinning towards basin margins in the west, southwest and east. The Rewanui also thins to the south where the basin is shallow (see 3.2.2(b)). Coarse greywacke conglomerates with a minor granite component predominate in the northwest and are well exposed at Twelve Mile Beach (Fig. 2), where Rewanui strata include rounded cobbles up to 0.5m in diameter and penecontemporaneous clasts of Waiomo mudstone more than 1m across. Rounded pebbles of coal occur in basal Rewanui beds at both 12 Mile Beach and 10 Mile Creek (Appendix 1). Sediments in the centre of the basin are quartzofeldspathic sandstones with a very minor greywacke component. Coal seams are thickest and most extensive near the top and bottom of the Member.

(d) Goldlight Member. The Goldlight Member thins towards basin margins in the east and southwest in common with other members, and ranges from 50 to 150m thick elsewhere. Thinning in the west and centre of the coalfield is largely a consequence of persistent accumulation of fluvial sediments in these areas; Rewanui deposition persisted relatively late and Dunollie sedimentation may have commenced early, both contemporaneous with Goldlight Member accumulation. The Member is absent in the far west. The Goldlight/Rewanui contact is usually well defined; however, the Goldlight/Dunollie contact is frequently highly gradational and precise designation of the boundary is an arbitrar exercise in many drillholes and sections. Gage (1952) inferred that, whereas the abrupt commencement of Rewanui fluvial sedimentation resulted from renewed tectonic activity, Dunollie fluvial sedimentation establishe gradually as a consequence of a declining rate of subsidence and silting-up of the "Goldlight" lake.

(e) Dunollie Member. The Dunollie is the most extensive Paparoa member. It exhibits similar overall thickness, distribution and facies changes to the Rewanui Member, with a coarse wedge of greywacke conglomerate in the northwest and predominantly quartzofeldspathic sandstones elsewhere in the coalfield. Feldspar tends to be less abundant than in the Rewanui, and workable coal is restricted to the Dunollie township area in the southwest (Fig. 2), where a seam was once mined near the top of the member. This coal has been noted for its low-volatile character compared with other Greymouth coals of similar rank (Wellman, in Gage 1952).

Dunollie sediments are distinctly fluvial but, with the exception of the coarse western facies, a relatively quartzose and even-bedded character compared with Rewanui sediments has been attributed to comparatively slow basin subsidence and low energy accumulation (Gage 1952). A dryer and/or warmer climate may also have prevailed, resulting in increased peat oxygenation and weathering of feldspars (Newman, J. et al. 1980). A reconnaissance study of coal type by the writer indicates that Dunollie coal exhibits an extreme range of coal microlithotypes, suggesting variable depositional conditions. Recent drilling has shown that the Member thickens abruptly southwest of Dunollie, where coal occurs (see 3.2.2 (b)). The possible tectonic and paleoenvironmental significance of this particularly interesting area of Dunollie sediments is briefly discussed in Appendix 2.

3.2.2 Basin Analysis.

(a) Introduction. Investigation of regional basin development and paleogeography at Greymouth has combined a study of coal measure thickness, texture, and composition. The thickness of successive members illustrates basin configuration and temporal evolution. Lateral variations in texture within individual members have paleogeographic significance, and compositional variations assist identification of sediment supply routes.

Recent drilling in Greymouth Coalfield has targeted the Rewanui Member. Members older than the Waiomo have been intersected in few holes, and relatively little has been added to the information documented by Gage (1952). Consequently, the Waiomo to Dunollie Members are emphasised in this section, particularly the coal-bearing Rewanui Member. Earlier members are discussed in cases where my interpretation of depositional history differs from that of Gage.

(b) Lateral Variations in Thickness. Gage's Paparoa CM isopachs indicate that the Jay and Ford Members were deposited in small southeast trending troughs (Fig. 13), whereas younger members accumulated in a single, relatively large, northeast trending basin. Recent drillhole data confirm Gage's reconstruction of the younger basin, except for complications in the unexposed southern part of the coalfield. Recent drilling (Fig. 12) contributes little to information on the Jay and Ford Members, however Gage's depiction of marked northern and southern limits to Jay and Ford accumulation is considered appropriate at least in the north, on the basis of exposed stratigraphic evidence (Gage 1952; Nathan 1978).

Gage's (1952) isopachs depict all Paparoa CM members as thinning abruptly towards a northeast trending line corresponding approximately with the eastern flank of the Paparoa Range. In the case of the Jay and Ford Members, Gage's isopachs were based mainly on outcrop, and should be most reliable in the north and northeastern areas where the members are well exposed. Gage shows an east-southeast trending trough of Jay and Ford sediments in the north of the coalfield that terminates sharply west of Blackball (Fig. 13), in an area where rapid thinning is in fact a consequence of recent erosion on the flanks of Mt Davy. There is no evidence that the original thickness declined in this abrupt manner. The members appear to have been

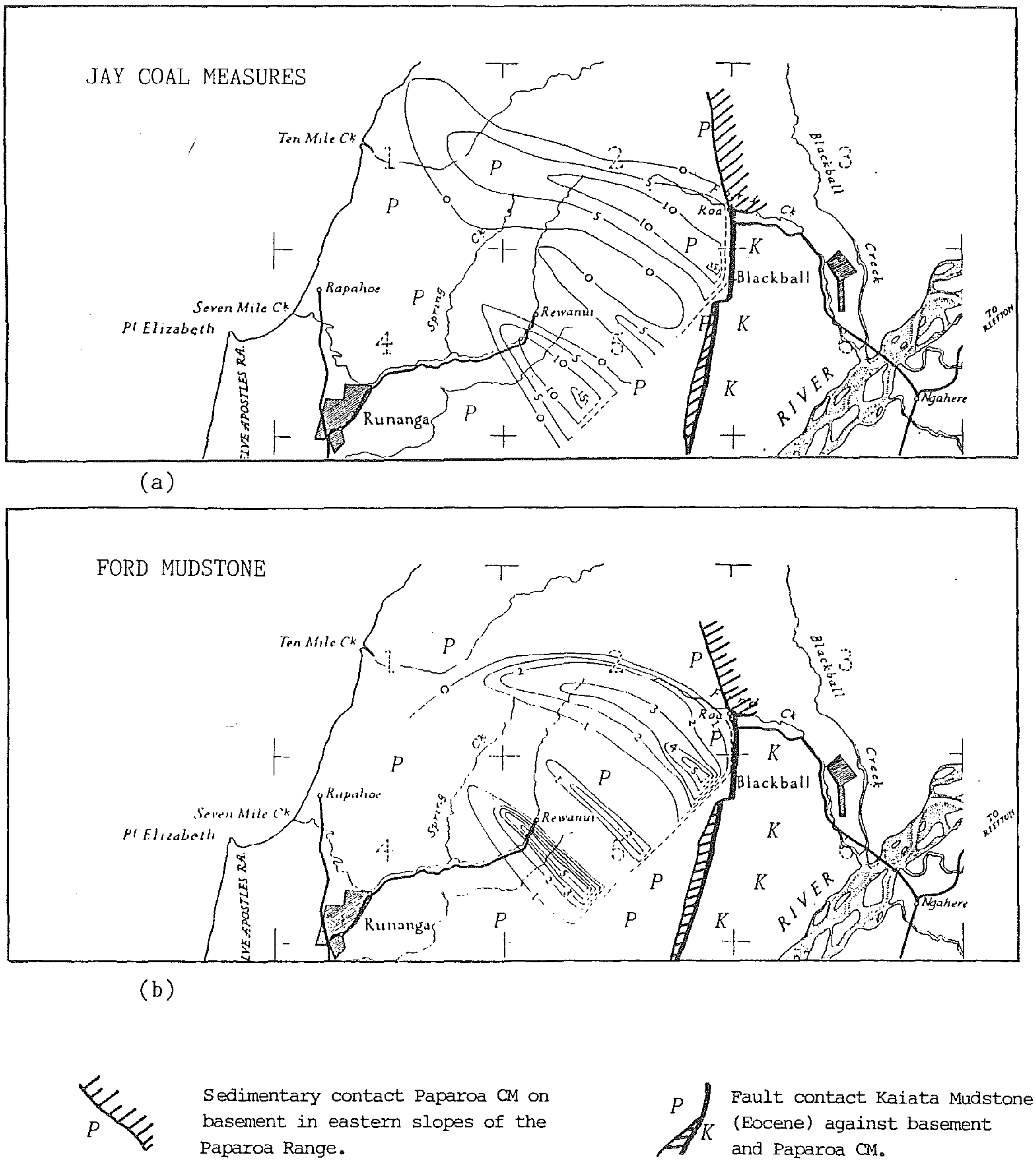


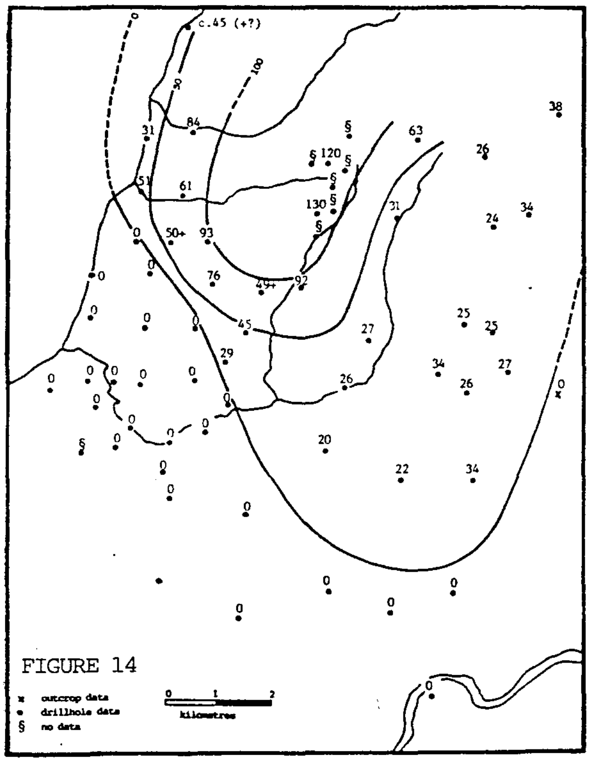
FIGURE 13. Gage's isopachs for the Jay and Ford Members of the Paparoa Coal Measures at Greymouth, with main geological elements sketched in for the eastern flank of the Paparoa Range. Both members are largely subsurface; outcrops are restricted to the north and northeast.

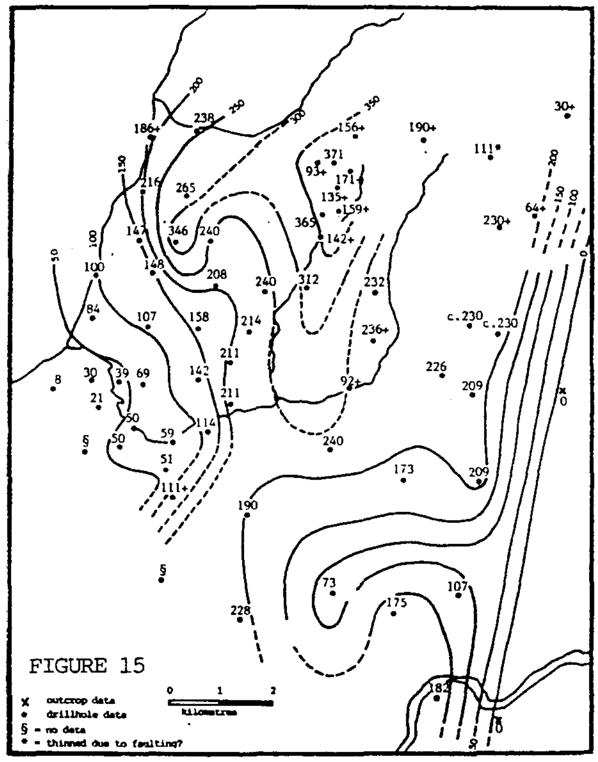
originally absent c. 4km further east along the trend of the trough axis, where Brunner CM rest directly on basement at Blackball, but this constraint is consistent with a much more gradual thinning rate than depicted by Gage.

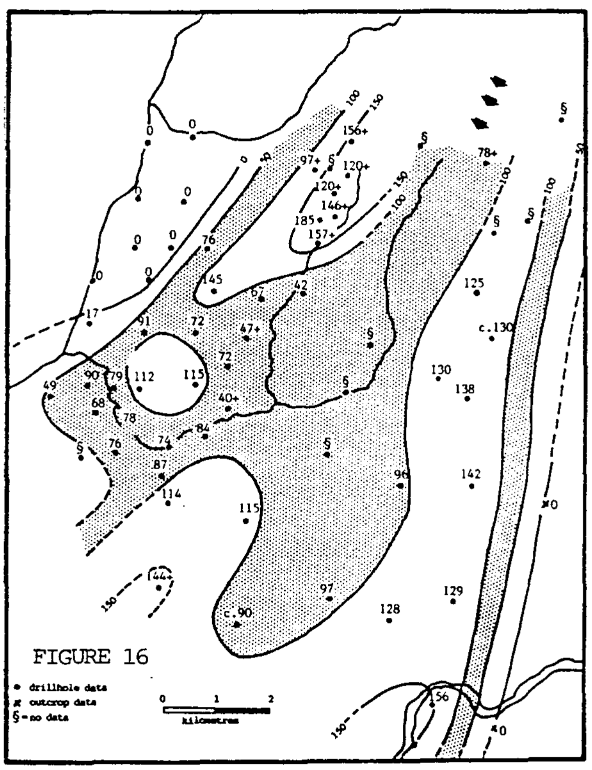
A deep southeast trending trough of Jay and Ford sediments shown by Gage southeast of Rewanui (Fig. 13) appears to be an extrapolation of drillhole data restricted to the Rewanui area, and thus is largely unreliable. This trough is sharply truncated in a subsurface location which appears to have been unexplored. I assume that the manner and site of thinning were extrapolated from the northern example discussed above, for which there can be no justification if the northern sediments terminate merely as a consequence of recent erosion. In summary: (1) the eastern truncation of both sedimentary troughs is interpreted to be an artifact of the isopach construction; (2) there is no direct evidence that sediments in the smaller southern trough are as thick as Gage indicates; (3) both structures are considered likely to have terminated more gradually than Gage's isopachs suggest. In particular, there appears to be no evidence for a well defined eastern limit to basin subsidence in the position suggested by Gage, and no good reason to invoke postdepositional denudation of Jay and Ford sediments as a consequence of uplift east of the Roa-Mt Buckley fault zone prior to Brunner sedimentation (Gage 1952, p. 18). Principal structural controls on early Paparoa sedimentation appear to have been oriented approximately northwest-southeast, and the pronounced north northeast trending margin which controlled later sedimentation was not developed at this time.

Structural controls on Morgan Member accumulation are unclear and recent faulting east of the Roa-Mt Buckley fault zone obscures the precise eastern limit of Morgan sedimentation.

In contrast with approximately northwest-southeast depositional trends in the Jay and Ford Members, Waiomo and younger members occupy a north-northeast trending basin and exhibit original thinning towards a well defined eastern margin. These trends are illustrated by isopachs for the Waiomo, Rewanui, Goldlight and Dunollie Members (Figs 14-17), prepared by the writer using both old drillhole data (Gage 1952; Greymouth drillholes 262-618, held by NZ Geological Survey and NZ Mines Division), and logs from recent holes compiled by Mines Division contractors, Lime & Marble Ltd (Fig. 12). Stratigraphic interpretation







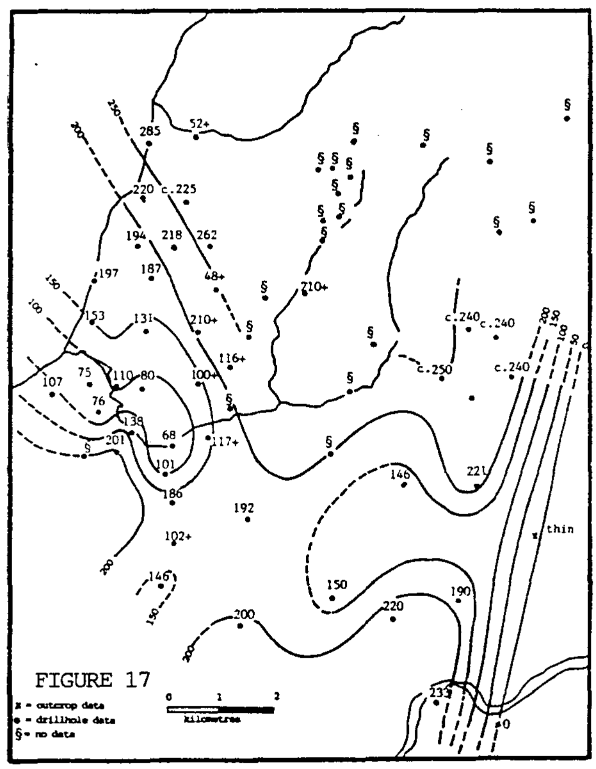


FIGURE 14. Isopach map for the Waiomo Member of the Paparoa Coal Measures

FIGURE 15. Isopach map for the Rewanui Member of The Paparoa Coal Measures.

FIGURE 16. Isopach map for the Goldlight Member of the Paparoa Coal Measures. Shaded area shows locations where the Member is between 50 and 100m thick. Thinning south of Seven Mile Creek and in the far east results from differential subsidence, and parallels thickness variations in the other members. Thin areas elsewhere result from supply of coarse sediment into the lake from west and northeast. Arrows indicate the direction of flow of the axial fluvial system, which is believed to have supplied sandy sediment to the centre of the basin during early and late lacustrine activity, while lake muds accumulated to the east, west, and south. 'Necking' of the thin area to the northeast, in the direction of coarse sediment supply by the axial fluvial system, may indicate that the northeastern entry into the basin was narrow.

FIGURE 17. Isopach map for the Dunollie Member of the Paparoa Coal Measures.

of the logs by the writer sometimes differs from that of the site geologists and details of these differences are recorded in full in Appendix 4. Major patterns depicted by the isopachs, particularly those which recur in successive members, are regarded as significant. Small scale, impersistent features, are attributed to structural complications.

The Waiomo Member (Fig. 14) is laterally extensive but thin, exceeding 50m only in the Spring Creek - Nine Mile Creek area. Although the Member occurs in the northwest at Twelve Mile Beach, western drillholes further south have been logged as lacking Waiomo. However, in several of these drillholes conglomerates do not appear until 50m or more above the base of what has been logged as Rewanui Member (Fig. 18). I consider that in this northwestern area, termination of the Morgan-Waiomo cycle of sedimentation is marked by conglomerates deposited when an alluvial fan prograded into a lake margin environment. The interval separating massive lacustrine mudstone (and locally basement) from the first appearance of substantial conglomerate is predominantly sandy, but generally consists of mudstones, sandy mudstones, and mudstones with sandy interbeds. In Drillhole 635, the interval is tuffaceous, a characteristic of Waiomo sediments in western areas. These mudstones and sandstones are inferred to represent proximal lacustrine - possibly lake shoreline - sedimentation which was contemporaneous with distal lacustrine Waiomo Member accumulation elsewhere in the coalfield. Stratigraphic subdivisions have been made accordingly (Appendix 4). The resulting pattern of Waiomo Member distribution is more consistent with overall basin configuration, as shown by cumulative Paparoa CM thicknesses (Fig. 19), than would be the case if the inferred marginal facies were excluded.

In contrast to extending the distribution of the Waiomo Member in the northwest, as discussed above, I would argue that its extent be restricted south of Sewell Peak relative to existing interpretations (Gage 1952; Greymouth Drillholes 266 and 273 held by NZ Geological Survey). In the area between Sewell Peak and the Grey River, three old drillholes - 266, 273 and 289 - remain an important source of data. Drillhole 289 encountered relatively thin Rewanui sediments overlying basement, as in the case of the recent nearby Drillhole 627. When logged, Drillholes 266 and 273 were interpreted to intersect Waiomo and Morgan Members before reaching basement; however, the "Waiomo Member" as described is only c. 10m thick and dominated by

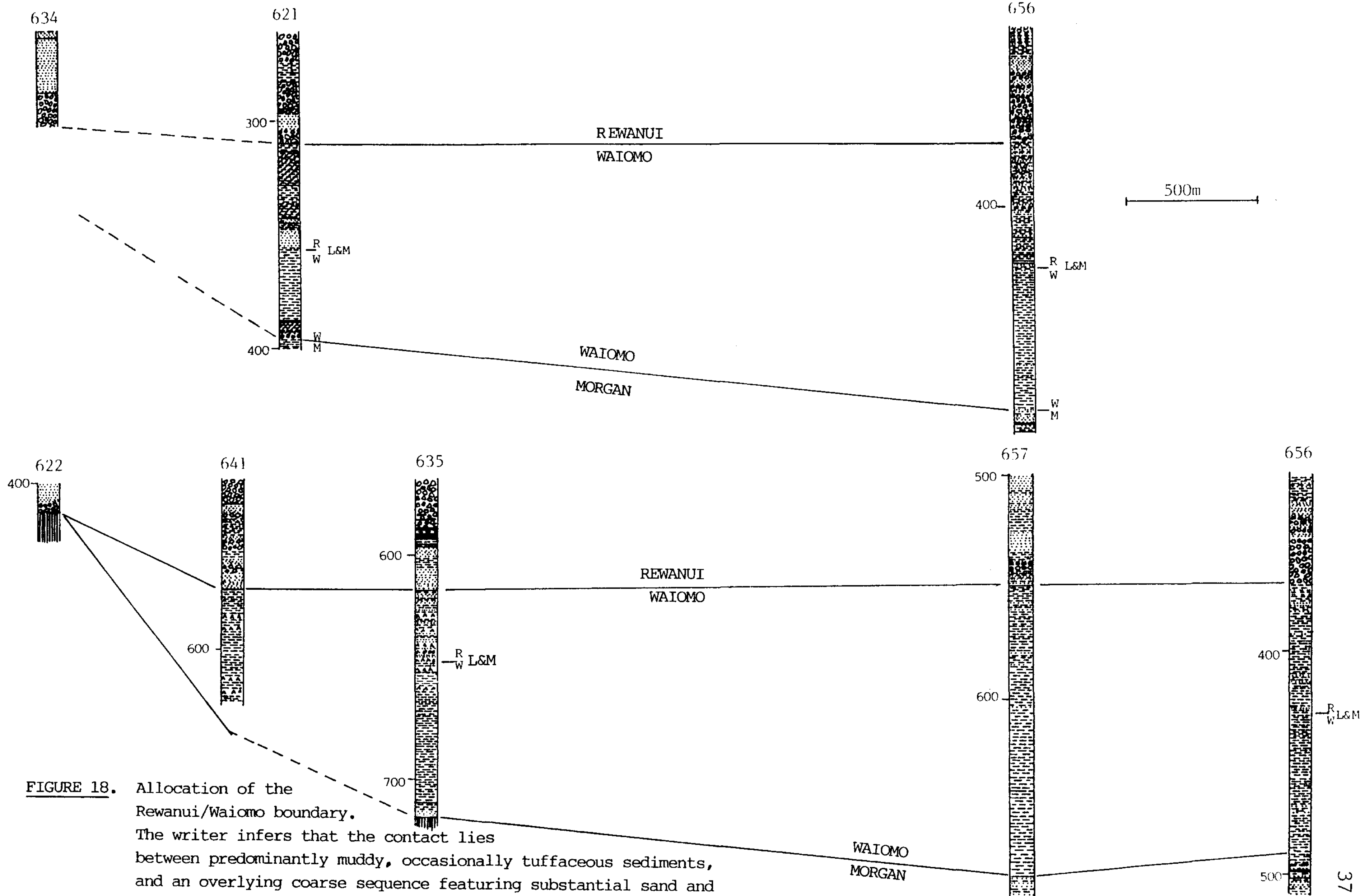


FIGURE 18. Allocation of the Rewanui/Waiomo boundary.
The writer infers that the contact lies between predominantly muddy, occasionally tuffaceous sediments, and an overlying coarse sequence featuring substantial sand and conglomerate. This subdivision is marked by a continuous line, and the stratigraphy of Lime & Marble Ltd is shown for comparison. Depths in metres.

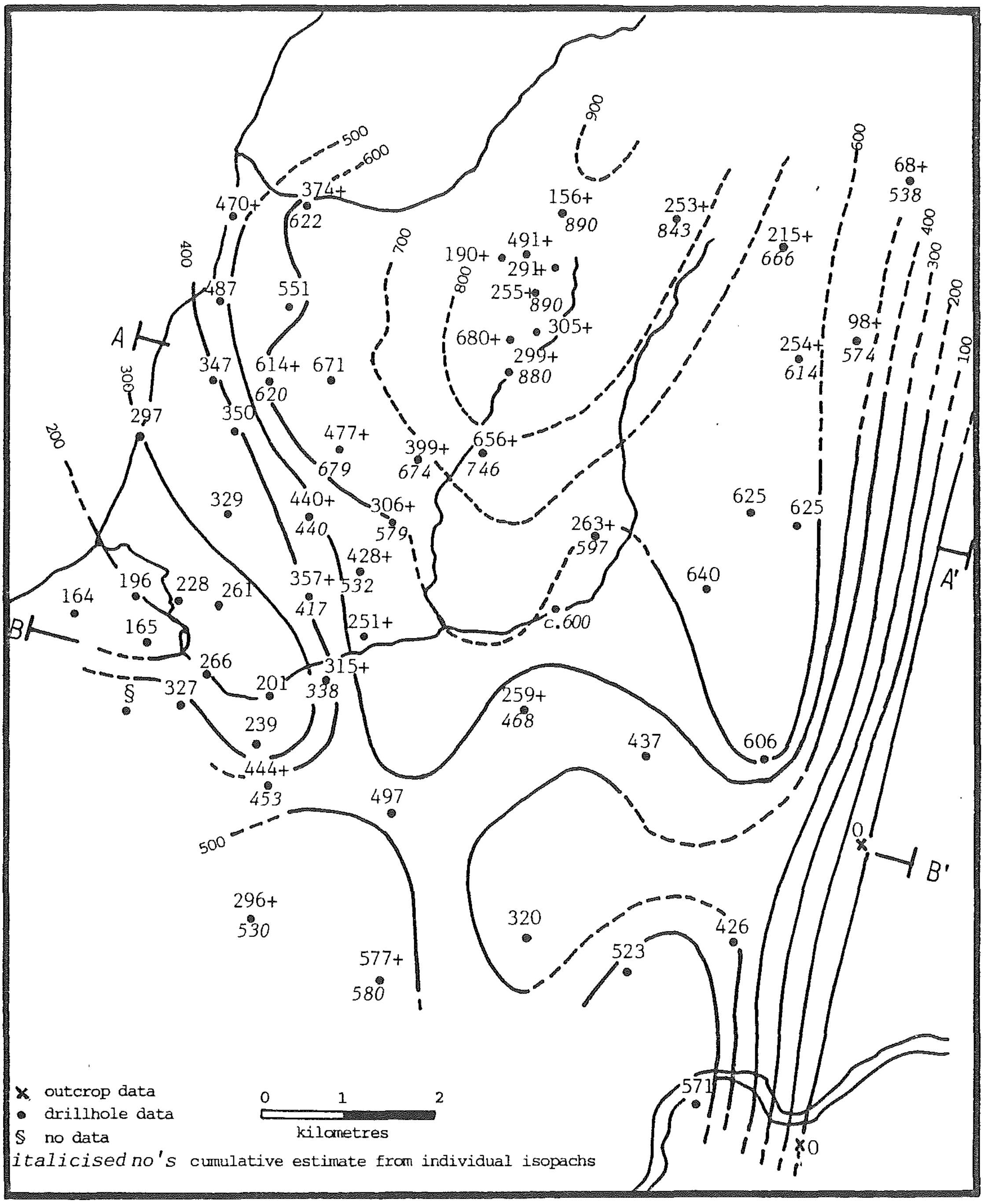


FIGURE 19. Cumulative isopach map for the Waiomo, Rewanui, Goldlight and Dunollie Members of the Paparoa Coal Measures.

sandstone, hence the subdivision may be unreliable. More importantly, the "Morgan" sandstones in Drillhole 273, of which several medium to coarse samples are available, contain abundant alkali feldspar (Appendix 5). For reasons discussed in a later section (see 3.2.2 (d)), these sandstones are attributed to the Rewanui Member on compositional grounds. ("Morgan" sandstone samples available from Drillhole 266 are very fine grained and quartzose, hence inconclusive with respect to allocation to a particular member). Therefore, the writer concludes that the Waiomo and Morgan Members do not occur much south of Sewell Peak.

Thickness of the Rewanui Member varies complexly across the coalfield (Fig. 15). Exposures on the eastern slopes of the Paparoa Range, little more than 1km away from drillholes which penetrated over 200m of Rewanui sediments, indicate that the Member wedges out rapidly to the east (Gage 1952). Recent drilling demonstrates that a much more gradual rate of thinning results in the Member becoming very thin (< 10m) in the southwest. The configuration of southwestern and southern limits of Waiomo Member accumulation are closely echoed in the Rewanui Member by patterns of thinning in the same areas. Rewanui sediments also thin to the northwest. Maximum thicknesses are achieved in the basin centre at the headwaters of Seven Mile and Spring Creeks. A local maximum south of Nine Mile Creek is not consistent with patterns of accumulation in earlier and later members and may result from fault repetition, or inclusion of a substantial thickness of sandstones laterally equivalent to the Goldlight Member.

The Goldlight Member thins to the southwest, south and east in a similar manner to the Rewanui Member (Fig. 16), and wedges out rapidly to the northwest where it is believed to pass into contemporaneous sandstones and conglomerates which cannot be differentiated from the Rewanui and Dunollie Members (Gage 1952). Definition of a contact between the latter two Members is difficult in the absence of an intervening lacustrine mudstone, and the boundary is now usually placed above the last substantially carbonaceous horizon. Raine (1981a) has demonstrated that the Cretaceous-Tertiary boundary lies within Goldlight mudstone at Seven Mile Creek, and that the boundary can be defined to within 10 - 30m in fluvial sequences of the western Drillholes 621 and 622 (Fig. 20). Delineation of this boundary at a larger number of sites would considerably assist stratigraphic subdivision and the preparation of chronostratigraphic isopachs.

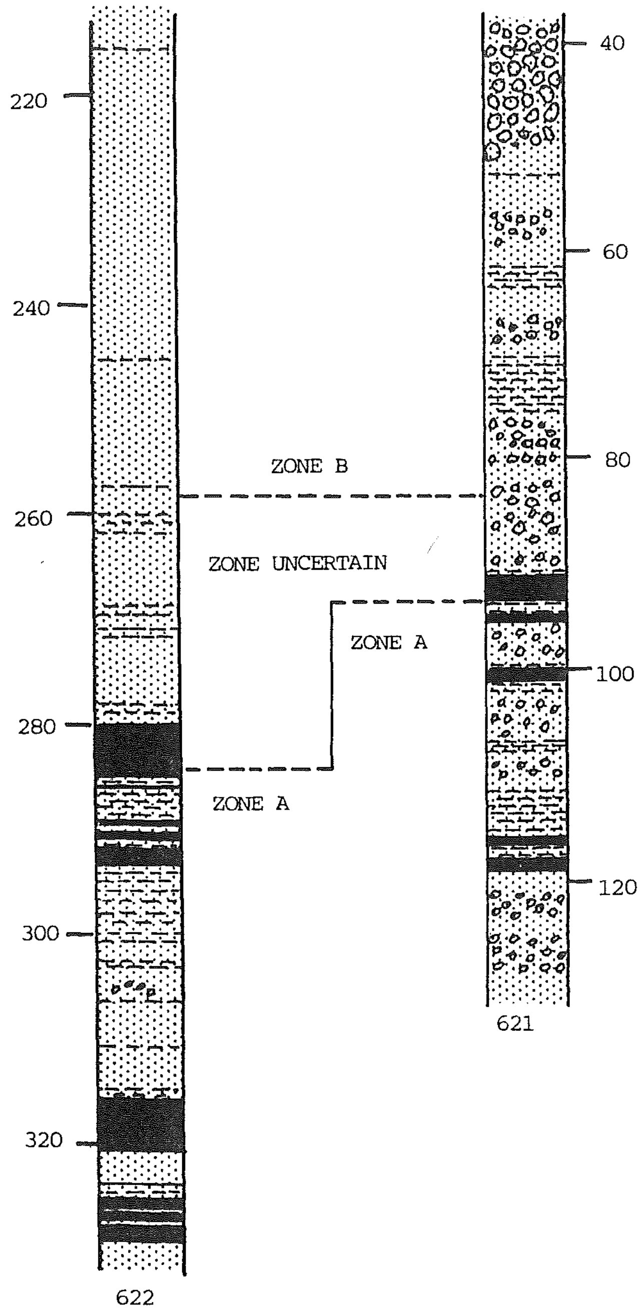


FIGURE 20.

Palynological identification of the Cretaceous - Tertiary boundary in Greymouth drill-holes 621 and 622. From Raine (1981a).

Whereas the contact between Goldlight and Rewanui Members is usually clearly defined, the base of the Dunollie Member is often gradational with considerable intercalation of lacustrine mudstones with sandstones. Definition of an upper boundary to the Goldlight Member is therefore somewhat arbitrary, and the subdivisions adopted by the writer differ in some cases from those assigned when drillholes were logged (Appendix 4). Complex variations in thickness of the Goldlight Member in the middle of the basin (from Dunollie to the headwaters of Seven Mile Creek) are attributed to diachronous upper and lower boundaries to the Member, resulting from coexistence of lacustrine and fluvial environments during lake transgression and regression (see 3.2.2 (f)).

Patterns of thickness variation in the Dunollie Member closely follow those of the Rewanui in the east, south and southwest, with the exception of an abrupt thickening south of the southwestern "basement high" where coal measures are thin (Fig. 17). This local thickening departs from patterns of thickness variation of earlier members and is discussed further in connection with Dunollie coal occurrences in Appendix 2. Recent erosion has thinned and in places removed Dunollie sediments in the centre and northeast of the basin, and the original maximum thickness of the Member consequently cannot be determined.

(c) Lateral variations in texture. As discussed in 3.2.2 (b), sandstones and mudstones underlying the lowest occurrence of Rewanui conglomerate in the northwest of Greymouth Coalfield are regarded as lateral equivalents of Waiomo sediments elsewhere in the basin. At Twelve Mile Beach (Appendix 1), indisputable Waiomo mudstone contains frequent interbeds of sandstone, as well as rare thin conglomerate in the upper part, and is inferred to have accumulated close to a western lake margin in contrast to more uniform mudstones in the centre of the coalfield. Gage (1952, p. 30) noted that "on the crest of the Paparoa Range north of Mt Watson the shale passes laterally into fine sandstone with bands of fissile shale showing ripple markings and rain pits" and inferred the presence of a lake margin nearby. I have observed that Waiomo mudstone exposed in the east below Mt Davy also incorporates a substantial proportion of sandstone, and an eastern lake margin appears to have been close by.

Textural variations in the Rewanui Member produce a gradual upward fining through the succession and pronounced lateral changes, particularly toward the west and northwest where conglomerate rapidly increases in abundance. Basal beds at Twelve Mile Beach include intervals of chaotic texture and structure strongly indicative of mass movement (Appendix 1). Given the large number of drillholes available, most of which are cored and logged in detail, a simple method of quantifying lateral variations in texture within the Rewanui Member is desirable. An isolith map has been constructed, depicting the cumulative thicknesses of conglomerate, sand, silt, mud and coal (Fig. 21). The accuracy of the textural map depends on the quality of the drill logs, which is good in the case of recent cored holes, less reliable in the case of a few open holes for which only geophysical

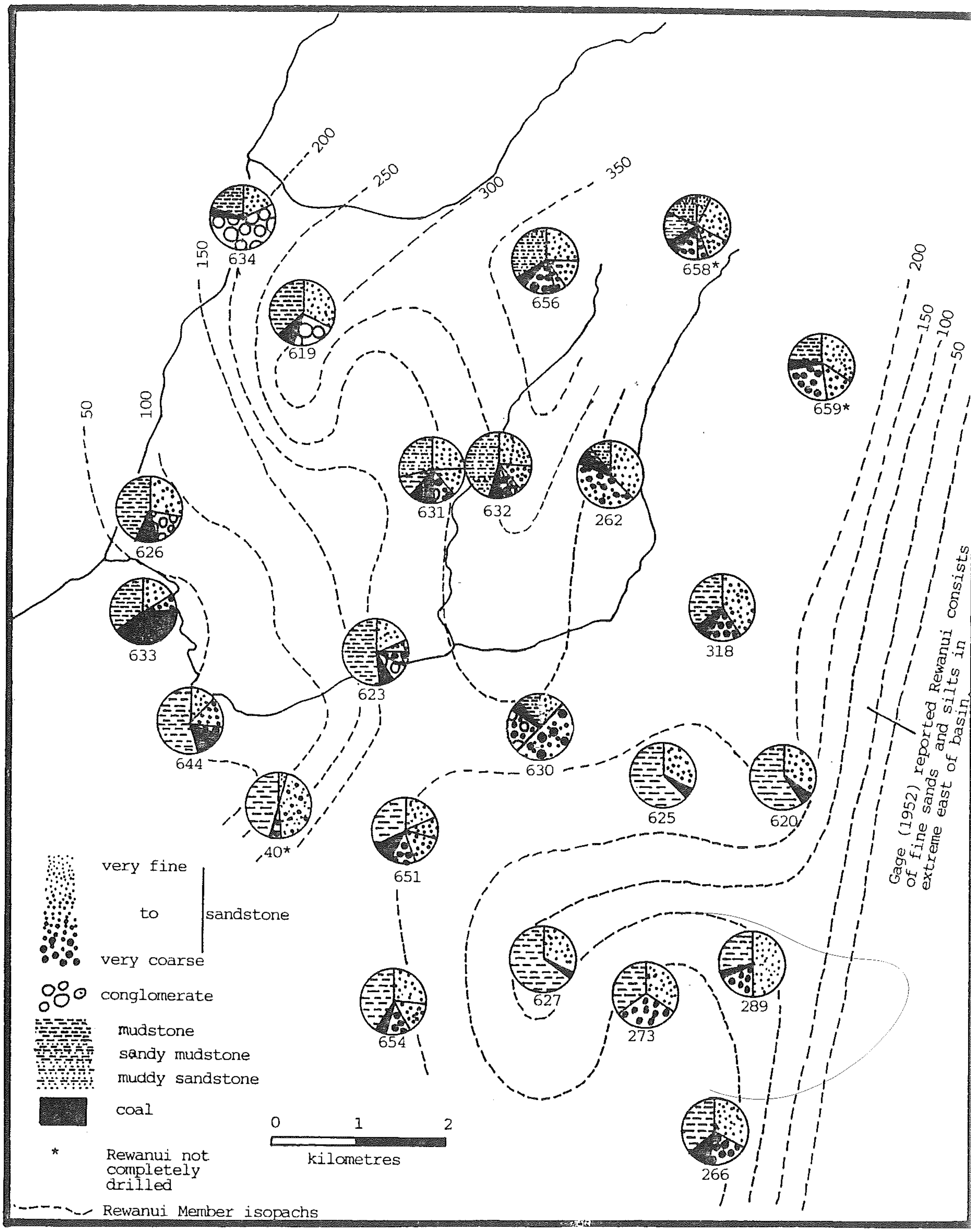


FIGURE 21. Lateral variations in texture of the Rewanui Member of the Paparoa Coal Measures, illustrating the cumulative thicknesses of mudstone, sandstone, conglomerate and coal for drillholes selected to provide good coverage of the study area. Data for Drillholes 620, 625, and 627 is based on geophysical logs and may be unreliable.

logs are available, and of unknown reliability in the case of cored holes drilled and logged many years ago, from which only sporadic samples were saved. Use of some old data has been necessary to adequately cover areas of interest, and one of the major inherent problems is consistency between the use of terms by earlier and later workers. For example, fine and coarse sand may once have been termed silt and grit respectively, depending on the logger. Subtle facies changes might be obscured by such inconsistencies, but major facies changes in the Rewanui Member are marked in spite of this problem.

Textural data from 23 drillholes in the Rewanui Member have been plotted as pie diagrams in Figure 21. In a few cases drillholes were terminated while still within the Rewanui Member and data are available only for the upper, relatively fine part of the sequence, as indicated in the figure. Drillhole data are not available for the far eastern margin of the basin, where Rewanui sediments are exposed in difficult terrain, but Gage (1952, p. 34) noted that:

> ....the Rewanui beds change eastwards near the eastern margin of the Paparoa deposition area into fine sands and silts indistinguishable from the marginal facies of Waiomo and Goldlight mudstone.

The writer has seen too little of the Rewanui Member in this particular area to confirm Gage's observation, but the data conform with well defined facies changes in Paparoa CM at Pike River Coalfield (see 3.3.5) and are incorporated into the general model of basin development (3.2.2(g)).

Drillholes 620, 625 and 627 in the southeast of Greymouth Coalfield were described by Lime & Marble Ltd from geophysical logs, on the basis that sandstone and mudstone produce low and high gamma traces respectively. The resulting lithological logs for all three holes have an unusually high proportion of mudstone (> 60%) which cannot be easily explained in terms of simple tectonic and paleogeographic models (3.2.2(g)). Examination of logs for nearby Drillhole 630, for which the lithological version was compiled with reference to a continuous core, demonstrates that although there is often a clear contrast between the gamma-log traces of sandstone and mudstone, occasional sandstones have an anomolously high gamma trace indistinguishable from that of mudstone in the same hole (Fig. 22). This result is attributed to unusually high concentrations of muscovite in the high gamma sandstones. It is impossible to determine the extent to

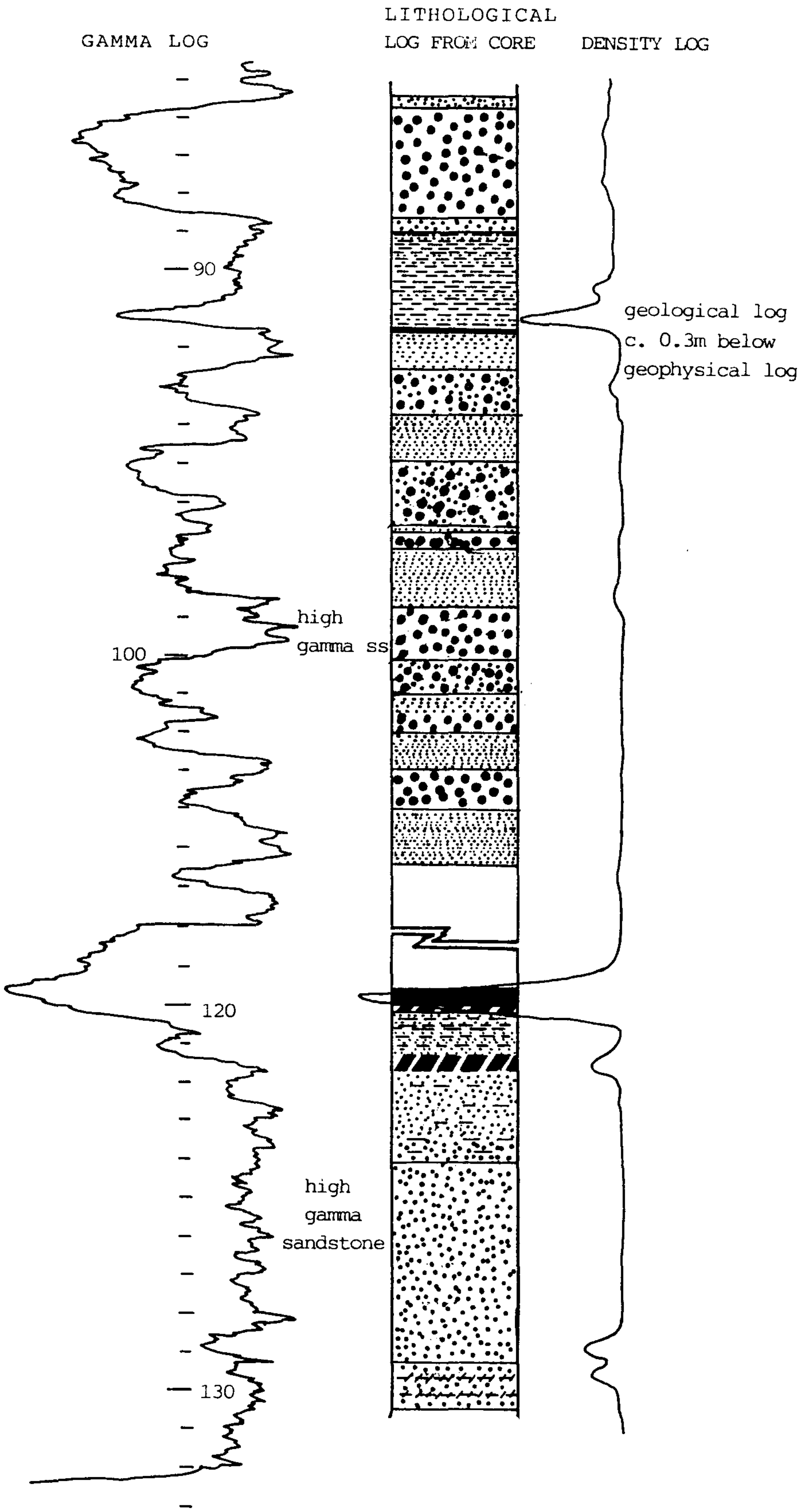


FIGURE 22. Evidence from Drillhole 630 that some Rewanui sandstones of granitic origin give high - gamma geophysical log traces and may be interpreted as mudstone where core is not available, as in Drillholes 620, 625, and 627.

which this phenomenon has resulted in over-representation of mudstone in the lithological logs for the three open holes, but comparison with textural data for nearby cored holes (Fig. 20) suggests that substantial bias may have occurred. This problem cannot be rectified without recourse to cuttings from the open holes.

Mudstone constitutes a very low proportion (< 25%) of Rewanui sediments in Drillholes 262, 659 and 630 (Fig. 22). The proportion is likely to have been similarly low in Drillhole 658 if the entire Rewanui Member had been penetrated, because the lower part is coarser than the upper. These five holes are located within an elongate north-northeast trending zone which is flanked to the east (e.g. Drillholes 318, 342, ?625 and ?620, and Gage's field observations) and west (e.g. Drillholes 623, 631, 632 and 656) by zones in which mudstone constitutes a greater proportion of the Rewanui Member. The succession becomes increasingly conglomeratic towards the northwest (e.g. Drillholes 626, 619, 656 & 634). Where the Rewanui becomes thin in the southwest, coal typically constitutes a high proportion of the sequence (e.g. Drillholes 633 & 644, and see 4.4).

In most areas, lateral variations in texture of the Goldlight Member consist of changes in the frequency of occurrence of sandstone beds. Gage (1952, p. 35) notes:

> Towards the northwest corner of the field the formation contains sandstone bands, becoming indistinguishable from the overlying formation. In the southeast it changes to dark siltstone and fine sandstone but is still recognisable.

He infers that these changes reflect proximity to lake margins.

Lateral variations in texture within the Dunollie Member are similar to those already described for the Rewanui.

(d) Lateral variations in composition. Studies of sediment composition by the writer have been restricted to hand specimen examination of conglomerates and sandstones, with limited support from sandstone petrography (Appendix 5). This work indicates that Jay and Morgan Member sandstones consist predominantly of Paleozoic greywacke (highly indurated lithic sandstone and shale) rock fragments and quartz, and that alkali feldspar in particular is absent. Jay Member conglomerates have only been observed to contain clasts of quartz and greywacke. These lithologies also predominate in Morgan conglomerates, in association with basalt in the east (Gage 1952) and hornfels and rhyolite in the northwest (Newman, J. et al. 1980; Appendix 1). The occurrence of rhyolite and tonsteins of pyroclastic origin in northwest Morgan sediments reflects acidic volcanism which may account for small quantities of alkali feldspar in Morgan sandstone from Twelve Mile Beach, as noted by D. W. Lewis (pers. comm.).

Granite derived lithologies first appear in the Rewanui Member. Rewanui sandstones in the centre of the coalfield are almost entirely quartzofeldspathic, with abundant muscovite. Most of the feldspar is weathered to varying degrees. Greywacke rock fragments are rare in this area, except locally near the base of the Member. Greywacke remains the dominant lithology in the northwestern conglomerates, but pebbles and cobbles of both granite and a coarse granitic sandstone are prominent in basal beds (Newman, J. et al. 1980) and granite constitutes 5-10% of pebbles throughout the sequence. Hence I infer that granite was locally associated with the northwestern greywacke source area. Reworked clasts of Waiomo mudstone (up to more than 1m diameter) and pebbles of coal also feature in basal Rewanui beds in the northwest (Appendix 1). Feldspar in northwestern Rewanui sandstones is typically angular and very fresh orthoclase and microline derived from northwestern granites. Dunollie sediments exhibit similar compositional variations to the Rewanui Member, but are generally more quartzose except in the northwest.

(e) <u>Paleoflow information for the Rewanui Member</u>. Paleoflow information is limited to sporadic observations in the northwest and north-centre of the coalfield and has not been collected systematically. However, observations of planar foresets and trough axis orientations in the headwaters of Seven Mile Creek, where Rewanui sediments are well exposed and dominated by current bedded sandstone, leaves no doubt that paleoflow was broadly towards the south in this area. Within the coastal greywacke conglomerate facies, a progressive increase in conglomerate abundance and clast size in a northwest direction clearly suggests a paleoslope from northwest to southeast and a northwest source for this material, as noted by Gage (1952). Seam configuration in the upper Rewanui at Strongman Mine (4.4) confirms that small streams running through the peat swamps flowed down a southeast-dipping paleoslope (Thorburn 1981).

(f) Tectonic controls on basin development. Gage (1952) recognised that the transition from coarse conglomerates in the Jay Member through fluvial sandstones with coal deposits to fine lacustrine sediments in the Ford Member represented a change from initial high relief associated with rapid sediment supply and coarse alluvial fans to progressively lower relief and reduced sediment supply terminating in ponding when sedimentation no longer kept pace with subsidence. Gage concludes (1952, p. 35):

> ....Ford silts were laid down in lakes caused by deformational impounding of fresh water in erosional late-mature valleys of the Jay landscape ..... To drown Jay valleys beneath non-marine water to depths ultimately exceeding 500ft involves the formation of an inland deformational basin of regional extent.

This interpretation implies that the Jay sediments accumulated in deep valleys originally incised ("erosional") by geomorphic processes, which were then flooded during regional downwarping. These mechanisms of basin development require *widespread* (i.e. "regional") uplift, erosion, and subsidence, whereas the actual distribution of the Jay and Ford Members (Fig. 13) indicates accumulation in sedimentary repositories that were laterally restricted. I prefer an interpretation whereby vertical fault movements produced multiple grabens elongated in a broadly east-west direction and of the order of 1 km wide. Such rifting is consistent with limited volcanic activity recorded as thin tuffs within Ford to Waiomo Members and very local basalt flows preserved in the Morgan Member. Alluvial fans derived from the upfaulted basin margins would fine upwards as initial relief declined due to erosion. Ponding would eventually result if the grabens had little external drainage and subsidence continued at a rate exceeding accumulation. This mechanism of basin development is consistent with rifting inferred to have controlled subsidence during accumulation of younger Paparoa CM Members, and readily explains the restricted occurrence of the lowermost Paparoa members. Gage himself was constrained to regard basin development as a potentially very localised phenomenon when considering the distribution of the eastern volcanic facies of the Morgan Member, and stated (Gage 1952, p. 28):

> It is difficult to account for the great thickness and at the same time the limited lateral extent of the igneous debris unless deposition was controlled by sharp local depression of the area immediately west of the fault of the Roa-Mt Buckley zone that was then active, and at no great distance from the centre of volcanic eruption. According to this view, a volcano arose on the elevated block to the east, but probably near the margin of the still subsiding western area.

He went on to invoke removal of the volcanic edifice from the elevated block by erosion. In fact it appears unnecessary to introduce the concept of a volcanic prominence in the east at all. Extrusion of basalt may well have occurred via fissure eruptions along the fault zone which constituted the eastern margin of the basin at this time, and construction of a volcano in the geomorphic sense could have been prevented by contemporaneous reworking of volcanic debris.

Lateral variations in the cumulative thickness of Waiomo to Dunollie Members (Figs 19 & 23) demonstrate a marked degree of differential basin subsidence, particularly in the east. Gage recognised a change from east-west to north-south basin orientation, but does

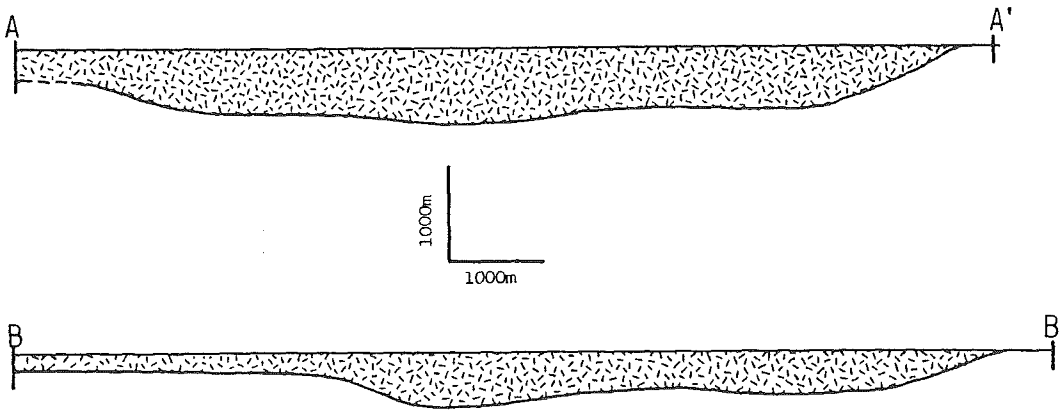


FIGURE 23. Cross sections through combined Waiomo to Dunollie Members of the Paparoa Coal Measures, Greymouth Coalfield. For section locations see Figure 19.

not discuss mechanisms of basin development except to point out, with reference to the eastern edge of the basin (Gage 1952, p. 29), that ".....this block remained a neutral member until renewed movements in Upper Paparoa times .....". Little more than 1km west of the stable block which formed this eastern basin margin, more than 600m of sediment accumulated by the end of Paparoa CM deposition. As Gage observed, this marginal block can never have been elevated far above the level of sedimentation within the basin, because it is capped by early Paparoa sediments (Jay - Morgan Members) which were preserved throughout deposition of the later Paparoa CM. In contrast the western margin of the basin, now offshore, is fronted to the east by a conglomeratic facies which coarsens to the northwest and was interpreted by Gage as the alluvial apron of an uplifted western block. The writer considers both margins to have been controlled by faults or fault zones bounding the basin, and on the basis of northwestern thinning and coarsening, the two margins appear unlikely to have been separated by more than 12 km.

The above model of a simple grabenal trough is shown by recent drillhole data to be valid only for the area north of Sewell Peak - Nine Mile Creek. The southern part of the basin has an irregular floor (Figs 19 & 23), reflected in lateral thickness variations which follow similar patterns in the Rewanui, Goldlight and Dunollie Members. Prior to accumulation of the Rewanui Member this irregularity is likely to have had some geomorphic expression, causing the observed southern and southeastern limits to the distribution of Waiomo and Morgan Members. Subsidence during accumulation of Rewanui sediments resulted in burial of whatever basement relief existed in the floor of the graben, and the fact that subsequent members also exhibit similar marked lateral variations in thickness indicates that basin floor structural deformation continued throughout Paparoa CM accumulation. Lateral variations in thickness within Goldlight and Dunollie Members are too large, in proportion to overall thickness, to be attributed to differential compaction of underlying coal measures which themselves vary in thickness merely as a consequence of original paleotopography. In addition, comparison of Figures 14 and 15 shows that Waiomo Member thickness is relatively unchanged at some locations where there are, in contrast, large thickness variations in the overlying Rewanui Member, as for example between Drillholes 625 and 620, and 622 and 639. There are two areas of particularly slow subsidence in the southern basin floor; the most pronounced lies in the southwest where Rewanui, Goldlight and Dunollie Members are all substantially less than 100m thick (Figs 15 to 17). During Dunollie accumulation renewed subsidence in the extreme southwest resulted in a rapid and unprecedented increase in thickness adjacent to the consequently laterally restricted, but still persistent, area of thin coal measures (Appendix 2).

Variations in thickness of the Goldlight Member are unusually complex (Fig. 16). The Member thins toward the southwest and southeast in a similar manner to the Rewanui and Dunollie Members, but fails to conform with the trends exhibited by these members in the centre of the basin. Abrupt thinning to the northwest is a misleading consequence of lateral transition to contemporaneous fluvial sediments (see 3.2.2 (c)) which are lithostratigraphically attributed to the Rewanui and Dunollie Members (Gage 1952). I attribute marked thinning of Goldlight mudstone in the Spring Creek area to persistence of Rewanui fluvial activity, fed by a northeastern source (see 3.2.2 (g)), contemporaneous with Goldlight lacustrine sedimentation elsewhere in the basin. This apparent abbreviation of the Goldlight sequence may have been accentuated by early onset of Dunollie sedimentation in the central area. "Necking" of the inferred fluvial lobe between its flanking zones of thick Goldlight mudstone (Fig. 16) suggests that the northeast-derived fluvial sediments may have entered the Greymouth basin via a restricted passage. This inference is consistent with the concept of basin development controlled by block faulting, which could result in abrupt narrowing of the trough to the northeast, structurally analogous with local restrictions known to flank Drillhole 627 in the south, as demonstrated by lateral variations in thickness of the Rewanui to Dunollie Members (Figs 15-17).

(g) Regional paleogeography and sedimentary history of the Rewanui Member. The main paleogeographic features believed to have influenced Rewanui Member accumulation in all parts of the Greymouth Coalfield are illustrated in Figure 24.

Gage (1952, pp 33 & 34) summarised his interpretation of Rewanui paleogeography as follows:

> An abrupt change to coarse sediments succeeding the Waiomo lake deposition suggests a sharp elevation of a neighbouring area, and from the observed regular increase in coarseness towards the northwest it is inferred that the source of the sediments lay in that direction. Granite-derived waste makes up the greater part of the Rewanui beds, in place of the greywacke material that characterised the lower coal measures, so that it may be inferred also that the northwestern source area consisted of granite mountains.

While it is true that most Rewanui sediments have a granitic source, the well exposed conglomeratic facies in the northwest is very largely greywacke derived, indicating that the northwestern source area consisted primarily of greywacke with only minor granite, contrary to Gage's interpretation. Following from this, the micaceous quartzo-feldspathic sandstones elsewhere in the basin cannot have a north-western origin, and another source area is therefore required. Cross bedding in fluvial sandstones exposed in the Seven Mile Creek catchment indicates paleoflow from the northern to northeastern sector (see 3.2.2 (e)). Granite does not currently outcrop south of Pike River Coalfield, and it is therefore probable that quartzofeldspathic sandstones at Greymouth were derived north of the Pike River area. Similarities in sedimentary history (see 2.3) and lithology between Paparoa CM at the two coalfields suggest that they were linked by a common fluvial system. In summary, sedimentation of the Rewanui Member is interpreted to have been controlled by two main paleogeographic

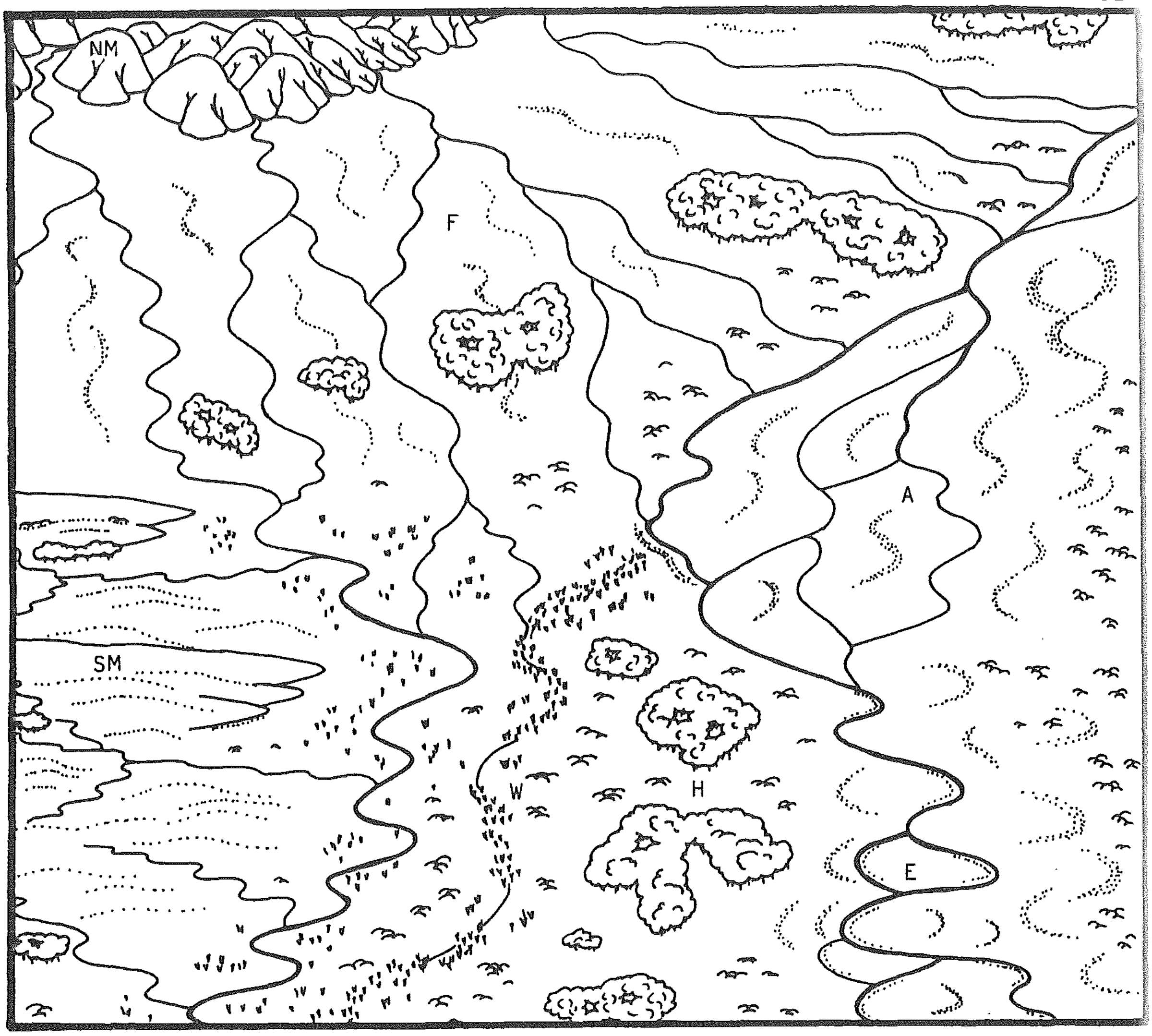


FIGURE 24. Synthesis of paleogeographic elements believed to have influenced accumulation of the Rewanui Member of the Paparoa Coal Measures, Greymouth Coalfield. The view is northward and shows the upfaulted northwestern basin-margin (NM) and associated alluvial fan (F), the emergent but low-lying southwestern margin (SM), the northeast-southwest oriented fluvial system flowing down the axis of the basin (A), the region of relatively slow subsidence (i.e., basement-high) which divides the basin in the south (H), and the resultant eastern (E) and western (W) arms of the basin which are hypothesised to have been occupied alternately by the axial fluvial system and by swampy flood plain.

elements. These were a locally important elevated greywacke terrain in the northwest associated with an alluvial fan of limited down-slope extent, and a major axial fluvial system flowing down the basin from the north to northeast.

The tendency observed by Gage for Rewanui sediments to fine towards the eastern basin margin (see 3.2.2 (c)) fits a general pattern wherein at and north of Drillhole 630, an axial zone dominated by coarse sediments is flanked to east and west by sequences containing higher proportions of mudstone (Fig. 21). The explanation for these trends is complex and in the case of the eastern basin margin information is limited, particularly because textural data derived from geophysical logs for Drillholes 625 and 620 is unreliable (see 3.2.2 (c)). Fortunately, similar trends occur in well exposed sequences at Pike River Coalfield and provide supplementary information. Between sections "2500N" and "1400N" at Pike River Coalfield (see 3.3.5), Paparoa CM Members 4 to 6 undergo a marked lateral change in facies from a sequence dominated by thick bedded granular coarse sandstone to a much thinner bedded sequence with finer sands and a much higher proportion of mudstone. Lenticularity of individual beds and a predominance of low angle trough cross bedding suggest accumulation in a braided fluvial regime, and limited paleocurrent data suggest that flow was towards the southeastern quadrant. The sequences at 2500N and 1400N are contemporaneous, and one area received mainly coarse channel sediments while less than 1 km away, measured perpendicular to paleoflow direction, relatively low energy deposits accumulated. Such rapid lateral changes in sedimentary facies if maintained over a substantial thickness, are unusual in fluvial sequences. Braided fluvial regimes are usually dynamic, undergoing frequent adjustments in the location of river channels, resulting in approximately even representation of channel versus floodplain sediments across paleoslope, at least over small distances (Miall 1977; Rust 1972). Clearly, some aspect of the Paparoa CM depositional environment prevented normal migration of river channels. This conclusion applies both to the Pike River Coalfield example and to Rewanui sediments on the eastern side of Greymouth Coalfield. As syndepositional faulting is considered to have controlled basin development at Greymouth during accumulation of Paparoa CM (see 3.2.2 (f)), to the extent that coal measures thin rapidly towards basin margins and over high areas within the basin, differential subsidence of the basin floor seems likely to have influenced river channel behaviour. Consequently it is suggested that, all other things being equal, channels tended to localise along zones of most rapid subsidence. To substantiate this hypothesis, a relationship should ideally be demonstrated between lateral variations in thickness of particular fluvial sequences (which indicate lateral variations in rate of subsidence) and the relative proportions of channel and overbank sediments constituting the sequences. With respect to the Greymouth example, available data are too limited to convincingly test the hypothesis, and at Pike River Coalfield structural complications at "1400N" prevent reliable assessment of thickness variations. Consequently, channel localisation due to differential subsidence cannot be considered proven, but it has been adopted as a viable working model. A similar model is implicit in Weimer's (1973) discussion of North American late Paleozoic to Mesozoic sedimentation in a horst and graben (i.e., rift valley) setting. Weimer indicates that river channels deposited coarse sediments in the grabens and fine overbank sediments on the horsts, implying an underlying tectonic control on facies distribution.

Further to the above discussion concerning the eastern part of the sedimentary basin at Greymouth, it is interesting that the proportion of mudstone in Rewanui sequences approximately doubles south of Drillhole 630 (i.e., in Drillholes 651, 654, 273, 289 & 266). (Drillholes 627, 625 and 620 are again neglected due to problems interpreting the electric logs - see 3.2.2(c).) There are two possible explanations for this southward increase in fine sediment. Firstly, the depositional gradient may have declined southward due to relatively slow subsidence in the southern area, resulting in a loss of momentum in the fluvial system and lower energy flow. Alternatively, or perhaps additionally, the zone of particularly slow subsidence about Drillhole 627 may have acted to deflect and localise principal channels to one side for long periods of time. For example, at a particular time principal channels may have flowed down the eastern "branch" of the basin (i.e., via Drillholes 273 & 266) while relatively fine sediments accumulated in the western branch during floods. Aggradation of the sediments in the eastern branch would eventually result in channel instability and avulsion into the western branch, after which fine sediments would commence accumulating in the east. This mechanism, which is reminiscent of construction and abandonment of deltaic lobes, appears likely to have been self-perpetuating. Persistent subsidence throughout Rewanui Member accumulation would ensure preservation of fine sediments, although as fluvial channels reestablished themselves in one or other branches of the trough some erosion of overbank sediments would undoubtedly occur. This model of channel localisation and alternation from one side to the other of a zone of retarded subsidence is an important element in paleogeographic interpretation at Pike River Coalfield, where preservation of thick peats in a braided river regime is otherwise difficult to explain (see 3.3.6).

The above discussion has been limited to Rewanui sediments in the eastern part of the basin where sedimentation occurred in association with a river flowing down the trough axis. During much of the time the Rewanui Member accumulated, this axial regime extended no further west than a line drawn through Drillhole 632 and a point slightly east of Drillhole 623 (Fig. 12). West of this line sedimentation occurred in association with streams draining southeast down the western alluvial fan. The junction between the two fluvial regimes is clearly defined in cored drillholes wherein western-derived quartz - (greywacke) lithic sandstones are readily distinguished from axially derived quartzofeldspathic sandstones (Fig. 25).

Most western-facies sequences southeast of Ten Mile Creek exhibit an association of contrasting coarse and fine sediments, which results in an often high proportion of mudstone and fine sandstone despite the presence of significant conglomerate (Fig. 21). Fine sediments are not characteristic of alluvial fan sequences, and their presence suggests that the northwestern alluvial fan environment passed down-slope into a lower gradient fan-toe area where alluvial processes were relatively low energy except during major floods. In the north, there appears to have been no shortage of sediment supply to either the western or the axial fluvial system during most Rewanui Member time, since the compositional interface remained stable within a c. 1 km zone of interfingering (Fig. 25). Towards the end of Rewanui Member accumulation this balance altered, and the axial fluvial system expanded approximately 1km further across the basin, taking in Drillholes 656 and 657. At this time Rewanui sedimentation in the western half of the basin became notably finer, and peat swamps were well developed as shown by one or more thick (4m+) coal seams in the upper Rewanui of several drillholes and at Strongman Mine. Rewanui sediments of the axial fluvial system are well exposed in the headwaters of Seven Mile Creek and exhibit an abrupt change near the top of the sequence from highly lenticular sandstone beds which characterise most of the sequence to laterally persistent tabular sandstones at the top (Fig. 26). This transition is inferred to indicate a change in fluvial regime, probably caused by reduction in paleoslope resulting from aggradation during transgression of the Goldlight lake northwards up the basin. The abruptness of the change in channel morphology suggests a very sudden alteration in depositional regime, and is considered likely to reflect adjustment from a braided to a meandering channel system. Meandering channels might tend to migrate further west than the preceding braided system, accounting for the wider influence of the axial fluvial system during upper Rewanui sedimentation. Alternatively, and perhaps additionally,

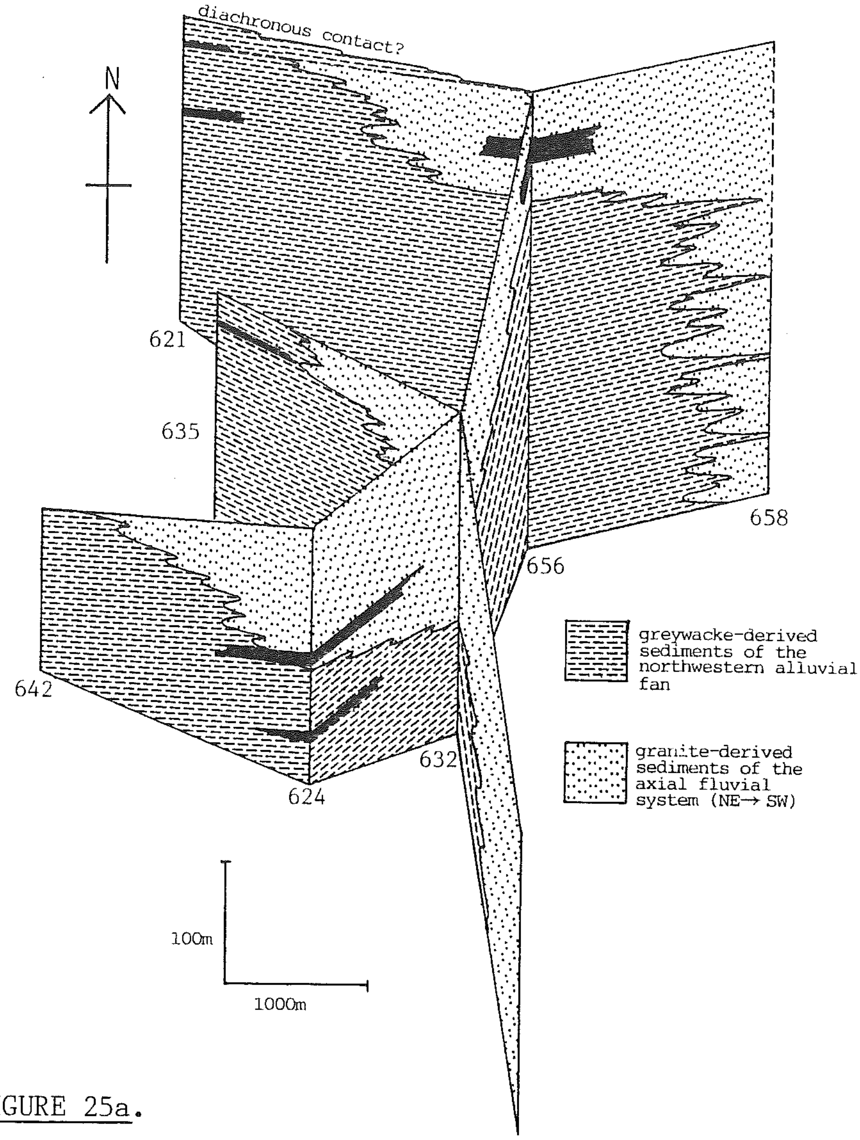


FIGURE 25a.

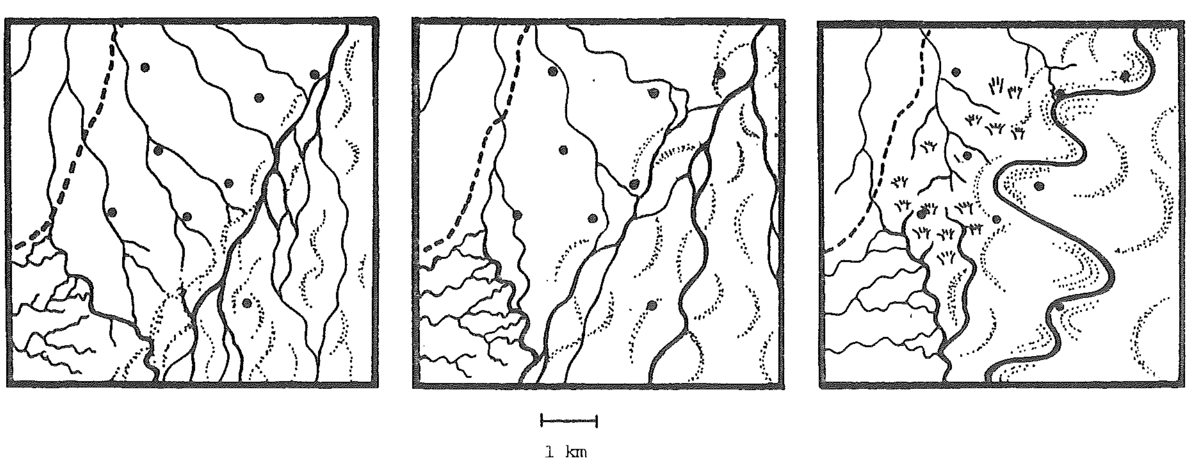


FIGURE 25b.

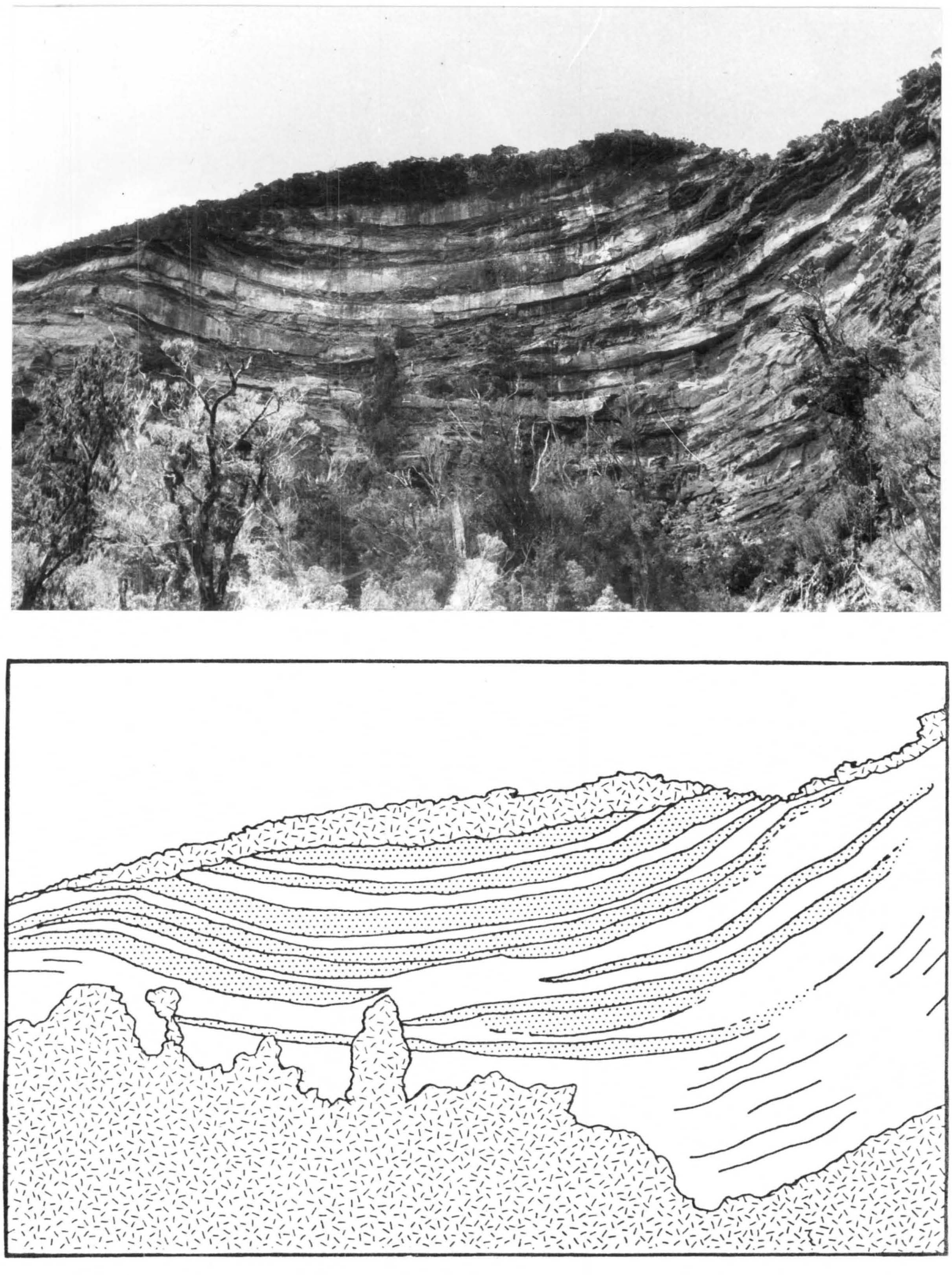


FIGURE 26. Rewanui Coal Measures exposed in the headwaters of Seven Mile Creek (on the south side of Carroll Creek near the junction with Waiomo Creek, map reference K32 372871). Prominent sandstone beds (stippled on sketch) exhibit a change from lenticular to tabular style in the upper part of the sequence. Although the lower strata in the exposure are principally sandstones they have not been stippled because individual beds cannot be differentiated.

the supply of sediment from the northwestern source may have declined rapidly, while continued subsidence attracted the axial system into the area. An earlier and more gradual decline in supply of northwest fan sediments is indicated for more southern areas, by compositional trends in the vicinity of Drillholes 624, 630, and 632. This distinction may reflect the greater distance of southern areas from the fan apex (Fig. 25b). The implications of upper Rewanui paleoenvironmental changes on peat accumulation are discussed in the following chapter (4.4).

One important sector of the coalfield has not yet been discussed. This is the southwestern "basement high" area, the part of the basin which subsided least during accumulation of the Rewanui Member. This area is notable for an abundance of thick coal indicative of extensive, long-lived swamps. Peat accumulation is inferred to have been particularly favoured in this region by restricted competition from fluvial sedimentation. Firstly, sedimentation may have commenced relatively late in the history of the Rewanui Member, when fluvial activity and sediment supply were less vigorous than previously. Secondly, fluvial systems contemporaneous with the peat swamps are considered to have been largely restricted to zones of more rapid subsidence in the north and east, rendering the southwestern area relatively remote from the most energetic flow conditions. Drillholes in the Spring Creek area (e.g., Drillholes 623 and 640) and south of Dunollie (e.g., Drillhole 649) confirm that seams are increasingly split by sediment bands towards zones of relatively rapid subsidence and active sedimentation. Section 4.4 more fully treats coal type, environments of peat accumulation, and lithostratigraphy of this southwestern area.

3.3 PAPAROA COAL MEASURE BASIN DEVELOPMENT AT PIKE RIVER COALFIELD

3.3.1 Introduction

Exposures of coal measures at Pike River Coalfield occur almost exclusively along the north to northeast-trending, west-facing escarpment (Fig. 4). For convenience of site description, an artificial base line has been defined (Bates 1981) which trends sub-parallel to the escarpment (Fig. 27). The origin of this line is Mt Anderson, designated 0m north and 5000m east. Section positions are described

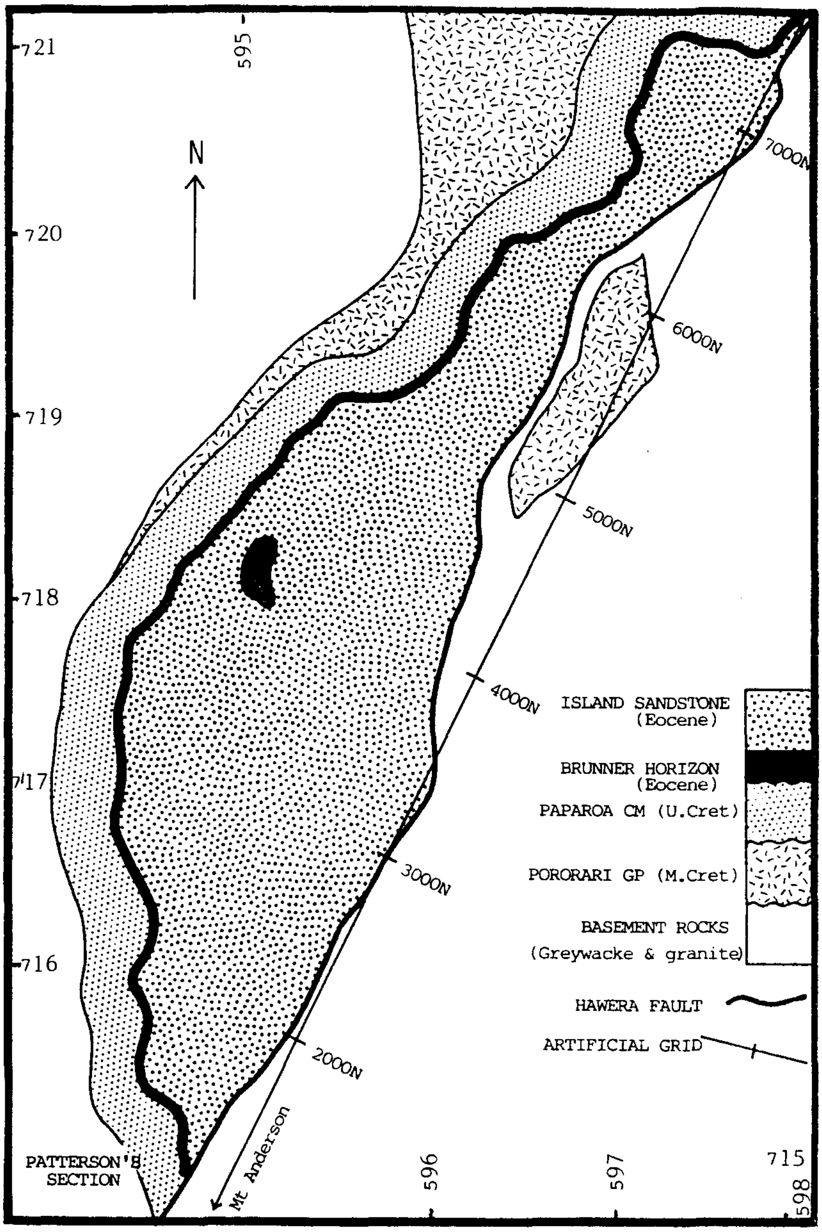


FIGURE 27. Simplified geological map of Pike River Coalfield, based on Laird (In press) and Bates (1981). Map grid refers to New Zealand 1 Mile Sheet (1:63360) 37 (Punakaiki).

in metres north of Mt Anderson (e.g., 2000N), along this base line.

Lateral variations in thickness and lithology of Paparoa CM members are less extreme at Pike River Coalfield than at Greymouth, partly because coal measures at Pike River are of limited extent and original basin margins are not represented. Outcrop is limited to the narrow escarpment, and there is virtually no drillhole data for unexposed areas.

Travel within the coalfield is slow and difficult due to rugged terrain and heavy bush and scrub cover. Although circumstances improved as exploration company personnel cut rough foot tracks, helipads and camp sites, access and weather conditions have continued to limit lithostratigraphic investigation to a reconnaissance level, and the following discussions of basin development are consequently limited.

3.3.2 Paparoa Member 1

Member 1 consists of weathered, subangular to subrounded, greywacke conglomerates of variable thickness (0-20m+) and uncertain age occurring between Paparoa CM and Pororari Group rocks in the centre and south of the coalfield (Fig. 8). Dating might result in allocation of these conglomerates to the underlying Pororari Group. If they are genuinely part of the Paparoa CM, they represent early basin subsidence associated with local relief on Greenland Group basement. The conglomerates are frequently absent, where M2 rests on basement or Pororari Group shales. This lateral discontinuity may result either from the infilling of original topography, or from differential subsidence caused by syndepositional faulting, as inferred for the conglomeratic Jay Member at Greymouth (3.2.2(f)).

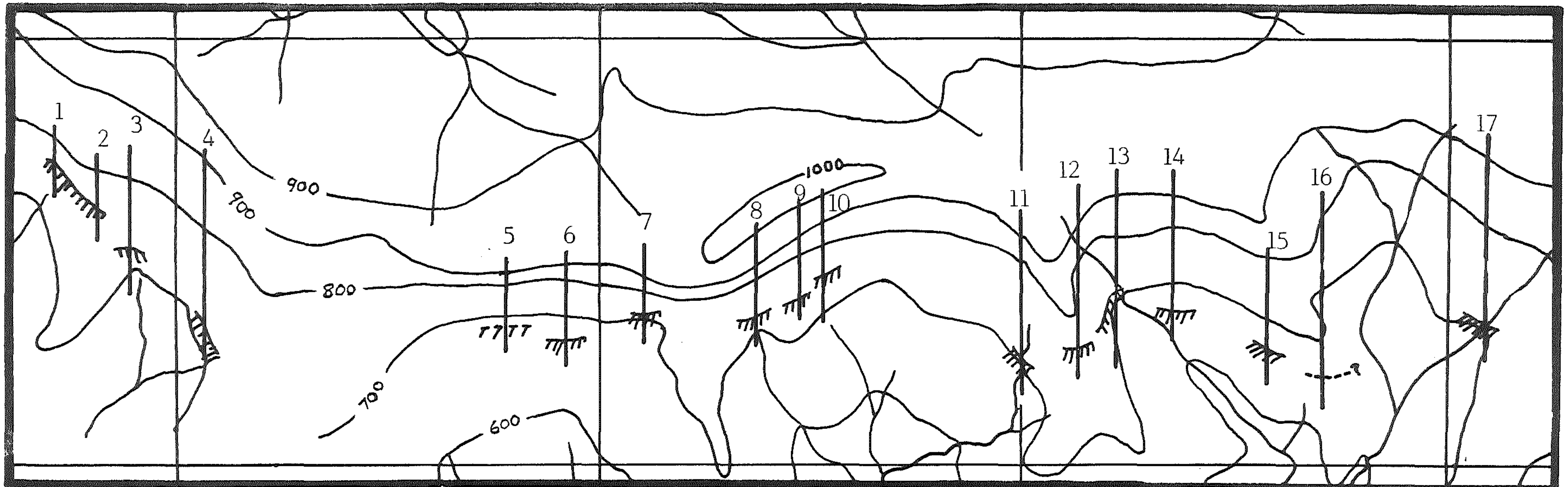
3.3.3 Paparoa Member 2

Member 2 (M2) consists of flow basalt, agglomerate and tuff, in varying thicknesses and proportions. Flows are characteristically localised and almost always underlie the pyroclastic deposits, which are much more widespread. M2 overlies Greenland Group basement, Pororari Group lacustrine mudstones, and greywacke conglomerates of M1, in different parts of the coalfield. The base of the Member is defined as the first appearance of volcanics. Thin tuffs also occur interbedded with lower M3 mudstones at a number of sites (Figs 28 & 29).

The total thickness of M2 ranges from nil to a maximum of at least 30m (Figs 30 & 31; incomplete exposure obscures the maximum thickness). Abrupt variations in thickness are demonstrated by the contrast between a section near 6800N and another 100m north (Fig. 32). At the latter, local basement (Pororari shales) was substantially lower, or subsided more rapidly, with the result that much thicker tuffs accumulated and were preserved, followed by several metres of lacustrine mudstone which are absent in the former section. (M3 is also relatively thick at 6900N.)

FIGURE 28. Tuff in mudstone below thick Member 3 coal seam at 6800N, Pike River Coalfield. Base of tuff at lower hammer head (T), tuffaceous element in mudstone dies out at upper hammer head. Coal seam commences at top of frame.

FIGURE 29. Detail of tuff in Figure 28. The pale, leached appearance of the very fine matrix, with blebs of darker material, is characteristic.



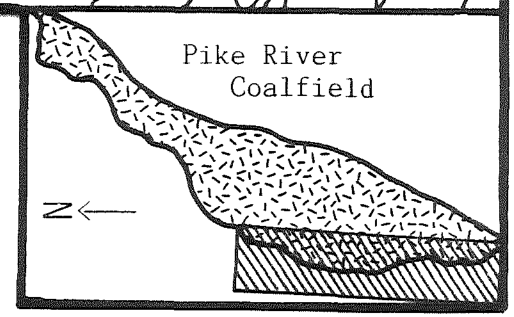


FIGURE 30. Location of sections illustrated in Figure 31.

Position of Figure 30 within coalfield is shown on inset map.
Grid interval 1000m*; contour interval 100m.

Basal contact of Paparoa Coal Measures

*(Grid = that used by Bates (1981)

FIGURE 31: Stratigraphic columns of Paparoa Coal Measures in the southern part of Pike River Coalfield. Figure 10 illustrates section locations. The thicknesses shown for the interval comprising Members 4, 5 & 6 are only estimated, whereas the thickness of Members 1 to 3 has been measured by the writer.

KEY

Members 4 to 6

Member 3

Member 2 tuff basalt

Member 1

Basement

not exposed = ?

coal in float

SCALE

50m

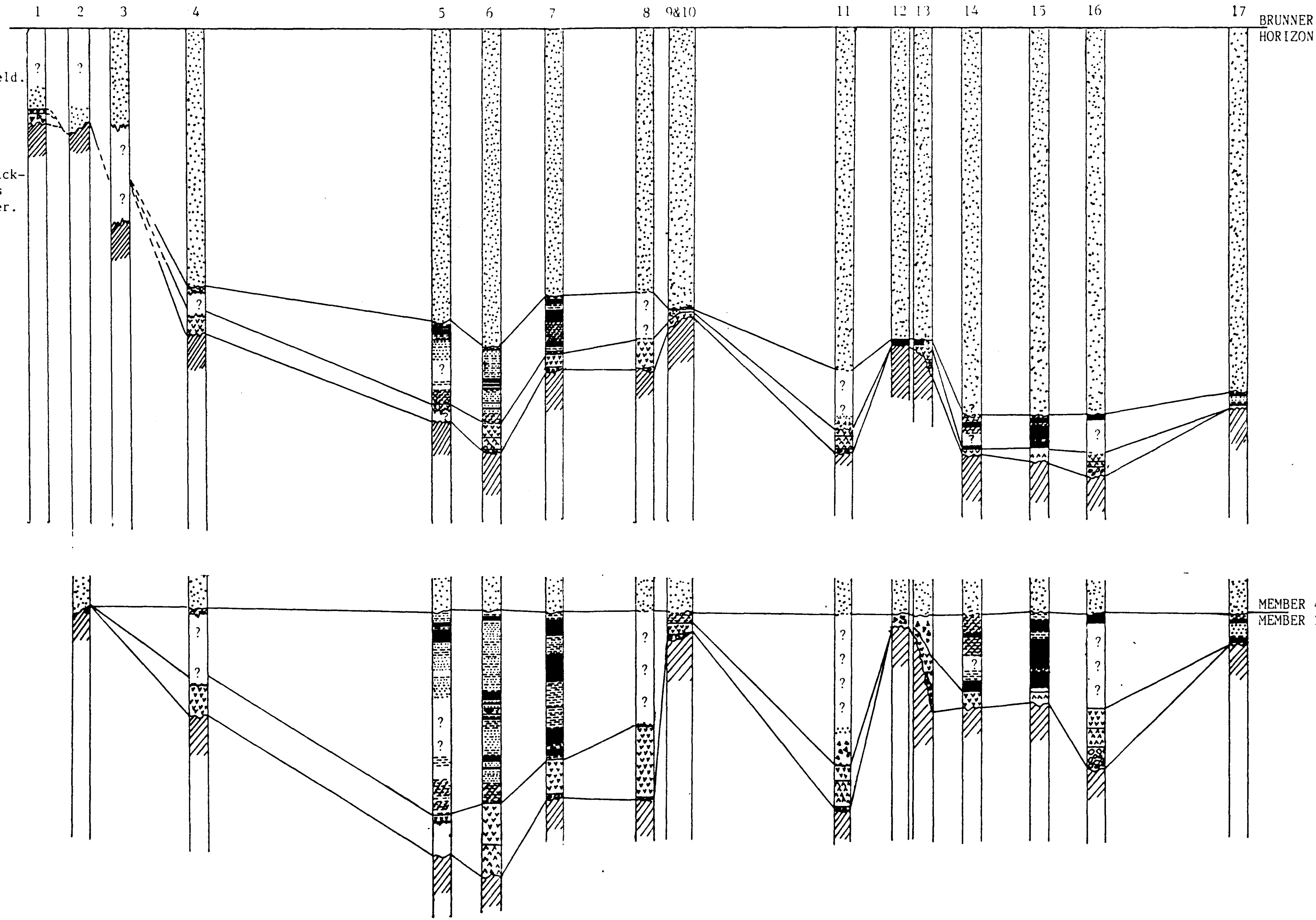
200m

For upper columns (Brunner Coal Measures to basement.)

20m

200m

For lower columns (Member 4 to basement)



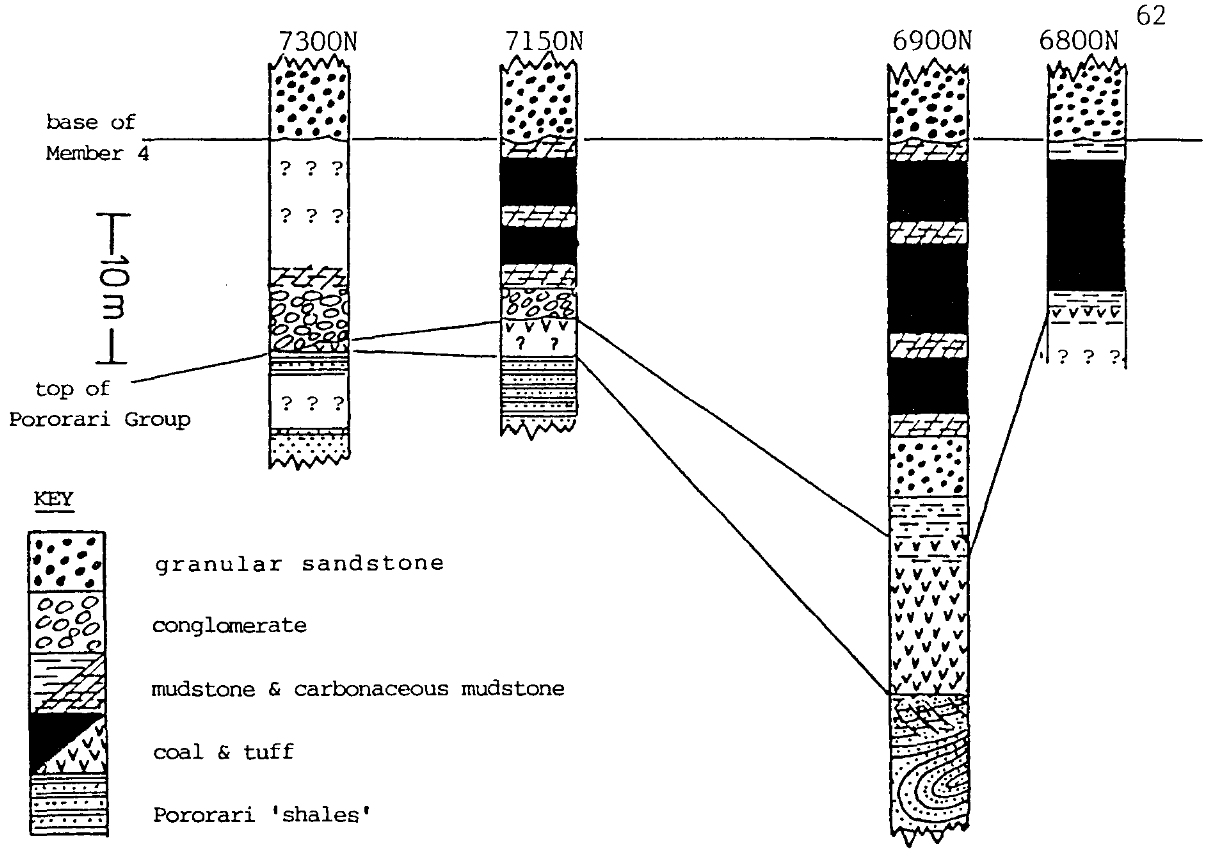


FIGURE 32. Lateral variations in Paparoa Coal Measure Members 2 and 3 in the north of Pike River Coalfield. Lithostratigraphic data are approximate.

The marked variations in thickness exhibited by M2 volcanics cannot be conclusively attributed to differential subsidence because control by paleotopography cannot be excluded. However, contemporaneous volcanic activity at Greymouth (Morgan Member) was certainly accompanied by syndepositional faulting, and presaged a change from east-west oriented basins of limited extent to a broadly north-south trending trough of regional extent, probably including granitic terrain in the Pike River Coalfield area (see 3.2.2 (g)). On this basis, it is suggested that syndepositional faulting and consequent differential subsidence, which can be more reliably deduced for subsequent members, probably commenced with the accumulation of M2. More direct evidence is provided by the adjacent sections near 6900N. Dramatic soft sediment deformation (recumbent folds, small faults, etc.) of mid Cretaceous Pororari Group shales beneath M2 volcanics in the thicker section (Fig. 32) supports the hypothesis that faulting occurred nearby during initiation of upper Cretaceous basin subsidence.

3.3.4 Paparoa Member 3

M3 comprises a variable sequence characterised by coal and carbonaceous mudstone, which rest conformably on and are often inter-beddded with uppermost M2 tuffs. Some sandstone is usually present, and in the far north of the coalfield a lens of predominantly greywacke conglomerate occurs near the base of the Member (Fig. 32). Below the conglomerate, tuffs of M2 are locally eroded, in which case the conglomerate rests on Pororari Group shales. The Member varies in thickness, sometimes quite rapidly, ranging from a few metres to approximately 50m. Coal constitutes 50% or more of M3 in some sections, and seams locally exceed 6m in thickness (Fig. 31). Examination of closely adjacent sections demonstrates a tendency for rapid lateral changes in Member thickness, sedimentology, and occurrence of coal (Fig. 32). The coals are locally dirty, due to a high clay content.

Variations in M3 thickness are frequently in sympathy with those of M2 (Fig. 31), hence likely to result from differential basin subsidence. Locally M3 is almost absent, and rests on very thin M2, indicating that subsidence had scarcely commenced at these sites prior to the more extensive movements which occurred when M4 accumulated. Variations in thickness of Members 2 and 3 are considered unlikely to have resulted from post-depositional erosion, because M4 has not been observed to contain reworked clasts of volcanics, mudstone or coal. In addition, post-depositional erosion cannot readily account for similarity in the lateral thickness trends exhibited by both Members 2 and 3.

Varying rates of subsidence during accumulation of M3 may have influenced sedimentation patterns to a limited extent, as indicated by an unusual abundance of sandy sediments where the Member is relatively thick at 3000N (Fig. 31). Stream energy must have been relatively high in this area, which may reflect localisation of principal drainage channels to zones of most rapid subsidence, an interpretation which is consistent with the model already proposed to explain facies changes in the Rewanui Member at Greymouth (3.2.2 (g)).

Elsewhere in the south, and in most northern sections, sand is a rare constituent of M3. Coal and carbonaceous mudstone are complexly interbedded, and although many seams are thick their persistence is commonly poor. Due to limited exposure it is difficult to trace individual seams, but examination of adjacent sections (Figs 31 & 32) indicates that coal grades laterally into contemporaneous carbonaceous mudstones. Peat is inferred to have accumulated in swampy depressions where sluggish streams wandered, occasionally ponding and overflowing into adjacent peat bogs (Fig. 33). This poor drainage, which is reflected by coal type characteristics (4.3) as well as lithology, may have resulted from accumulation in a complex post-volcanic terrain characterised by confused paleoslopes with ill-defined and discontinuous drainage paths.

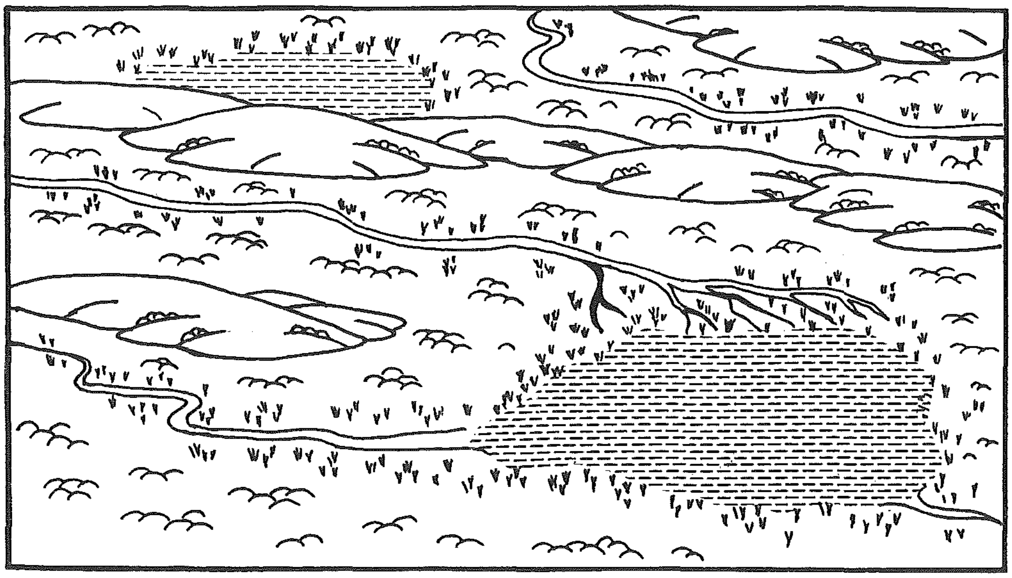


FIGURE 33. Diagrammatic paleogeographic interpretation for Paparoa Member 3, Pike River Coalfield. The Figure is a generalisation, not intended to represent the location of specific streams, etc.

3.3.5 Paparoa Members 4, 5 & 6: Introduction

The upper three members of the Paparoa CM at Pike River Coalfield constitute a thick fluvial sequence which undergoes marked lateral changes in thickness, attributed to differential subsidence resulting from syndepositional faulting. The sedimentological character of all three members, e.g., the predominance of very low angle and trough cross bedded sandstone, and the lenticularity of individual sandstone beds, is more akin to braided stream deposits (e.g., Malbaie Fm, Rust 1978) than meandering. However, detailed studies are warranted, particularly of M4 sequences which are unusual in their paucity of mud yet abundance of coal. Lateral facies changes commonly occur and are particularly marked in the south of the coalfield, where thick bedded, conglomeratic granular sandstones in the vicinity of

2500N (Fig. 34) pass laterally into contemporaneous but much thinner bedded and finer sandstones interbedded with mudstone at and south of 1400N (Fig. 35). This facies change, which is particularly marked in Members 5 and 6, can only have resulted from localisation of principal channels in the area now dominated by coarse sediments. Away from principal channel loci, sand accumulated only during major floods, or at times when channels diverged from their usual path, and these sands are thinner and often finer than those of the main channel deposits. At other times, mudstones accumulated away from the main channel axis. This tendency for channel localisation has been discussed with reference to the Rewanui Member at Greymouth (see 3.2.2 (g)), and a working model has been erected whereby major channels tend to localise along zones of most rapid subsidence. Unfortunately, lateral variations in original thickness of the Member 4 to 6 sequence, which according to the model should decrease southward as the lithofacies becomes finer, cannot be reliably determined due to thickening of southern sequences by fault repetition adjacent to the Hawera Fault thrust zone. The sequence thins markedly north of the coarse facies at 2500N (Fig. 31), but any corresponding facies changes cannot be examined due to poor exposure.

3.3.6 Paparoa Member 4

M4 consists predominantly of thick bedded, quartzofeldspathic and greywacke-lithic granular very coarse sandstone (Fig. 36), which is frequently conglomeratic. The sandstones commonly exhibit horizontal lamination, very low angle cross bedding, and trough cross bedding in sets up to c. 0.5m thick. In most parts of the coalfield, mudstone and siltstone are a relatively minor component, usually occurring in beds 1 - 2 m thick in contrast with the 3 - 5m sandstone beds and coal seams which locally exceed 3m in thickness. The succession is thus unusual for a fluvial association in being dominated by coarse clastics and coal and deficient in fine clastics. Most seams have roofs scoured by overlying channels infilled by sandstones (Figs 37 & 38) and vary laterally in thickness as a consequence. Locally (e.g. 6450N), the sandstone beds are finer, relatively thin (< 2m), and associated siltstones, mudstones and coals constitute a higher proportion of the sequence (Fig. 38).

Basal M4 beds usually scour underlying M3 mudstones. The contact is defined as the transition from thick carbonaceous mudstones

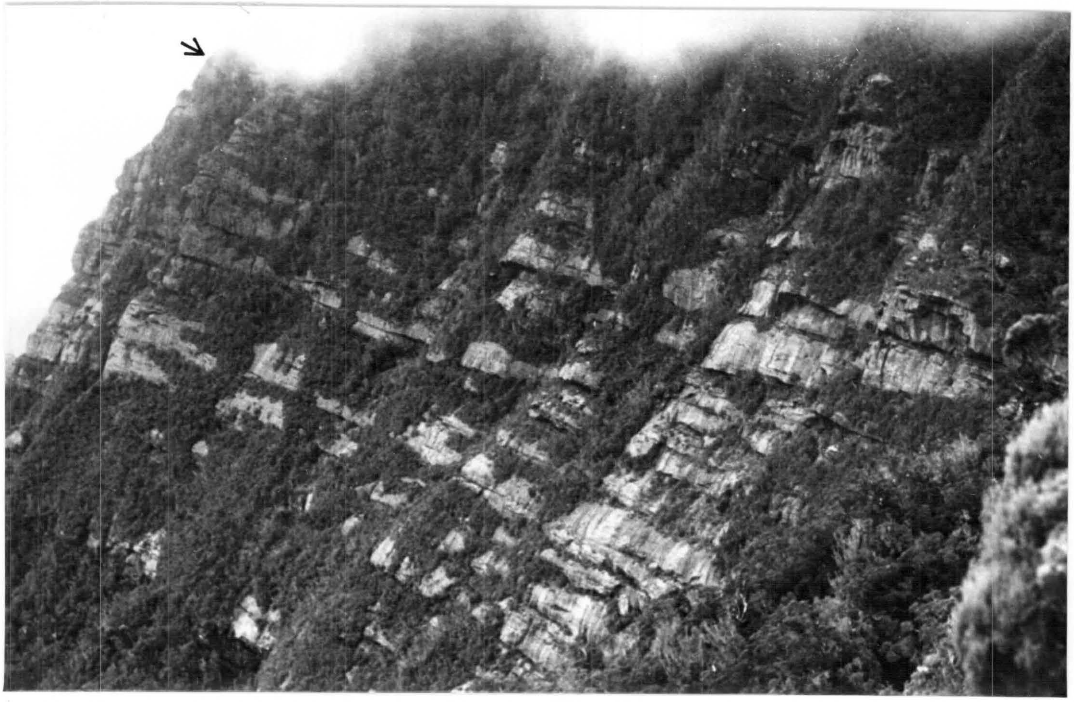


FIGURE 34. Coarse, thick-bedded 'channel' facies of Paparoa Coal Measure Members 4 to 6, at 2500N, Pike River Coalfield. Approximately 200m of Paparoa Coal Measures are exposed beneath the Brunner horizon (arrowed).

FIGURE 35. Relatively fine, thinner-bedded facies of Paparoa Coal Measure Members 4 to 6, at 1400N, Pike River Coalfield. Approximately 200m of Paparoa Coal Measures are exposed beneath the Brunner horizon (arrowed). Negative reversed before printing for ease of comparison with Figure 34.

FIGURE 36. Trough cross-bedded granular very coarse sandstone of Paparoa Member 4, exposed in ridge at northernmost end of Pike River Coalfield (7250N).

FIGURE 37. Coal seam with scoured roof in Paparoa Member 4 at 7250N, Pike River Coalfield.

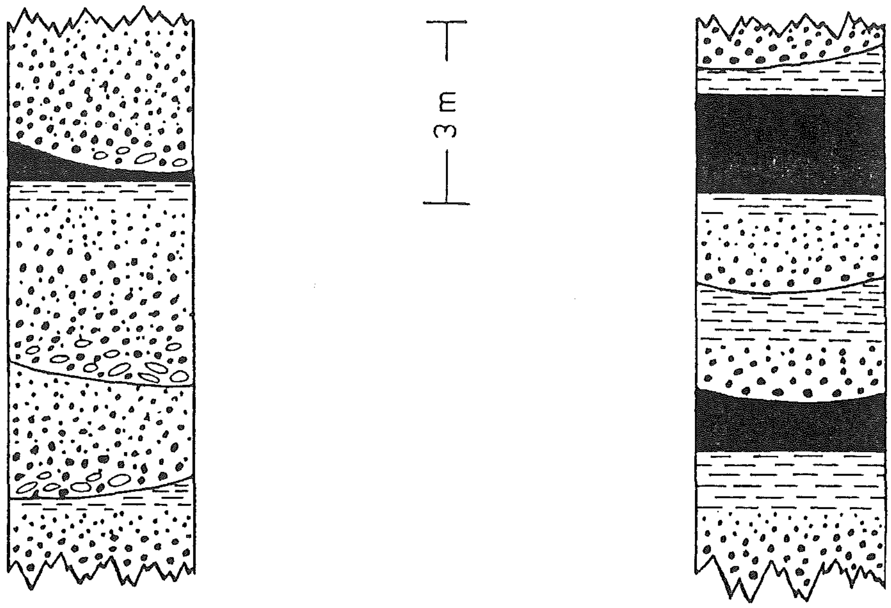


FIGURE 38. Diagrammatic illustration of contrasting lithofacies in Paparoa Member 4, Pike River Coalfield.

of M3 to thick granular sandstones of M4. Locally the contact is gradational due to the early appearance of granular sandstone interbedded with upper M3 mudstone.

The facies changes discussed in 3.3.5 are less marked in M4 than in succeeding members. M4 is predominantly coarse and thick bedded in most of the coalfield, and it is therefore remarkable that the Member contains many coal seams. In contrast, coal is virtually absent from Members 5 and 6. Sedimentation of M4 in most areas appears to have occurred during episodes of high energy flow resulting in very coarse sand accumulation, followed abruptly by abandonment of fluvial channels and subsequent peat accumulation. Thick clean peat accumulation requires very long periods of protection from sediment-laden flood waters, and the occurrence of coal seams in M4 indicates that peat swamps at times became established and persisted for long periods in areas which at other times were occupied by major channels. For this to be possible, flow must have locally declined to a comparativ trickle for many thousands of years. The necessary alternation of high energy fluvial activity, with fluvial inactivity during peat accumulation, is difficult to achieve in the case of a braided river system. It is necessary to infer either that each high energy fluvial episode occurred in response to transitory uplift in the source area, or alternatively that fluvial activity did not decline everywhere while peat accumulated but was merely diverted away from potential swamp areas for very long periods. The former interpretation of episodic tectonism is not favoured. However, an area of relatively slow subsidence in the centre of the field is demonstrated by thinning of Paparoa CM over a basement high between c. 3600N and c. 5000N (Fig. 39), and this may have been responsible for intermittent containment of fluvial activity to one part of the coalfield, while other areas were left free for peat accumulation. I suggest that the fluvial system flowed preferentially along the zones of relatively rapid subsidence which occurred north and south of the basement high. However, instead of occupying both sides simultaneously, the river must have occupied one side at a time. Aggradation of river channels due to active sedimentation on one side would eventually cause instability of the channel path and consequent avulsion into the now relatively low lying alternative route, where only peat and fine sediment suspended in flood waters had been accumulating for the duration. After avulsion, peat and fine sediments would accumulate in the zone previously occupied by the fluvial system, until such time as aggradation in the new fluvial locus caused instability and a change back to the original path (Fig. 40). This model has already been invoked and discussed in greater detail in connection with sedimentation of the Rewanui Member south of Sewell Peak at Greymouth (see 3.2.2 (g)), and also is supported by the configuration of M4 coal seams in the southern half of the coalfield. At Patterson's Section (Fig. 27) four seams occur in M4, three of which exceed 2m in thickness. Seams become thinner and fewer in number northward, and where exposure permits, a scoured roof can be seen or inferred in most cases. Coal is virtually absent in the coarse channel facies at 2500N, although very thin, scoured seam remnants are locally exposed near the base of the Member. This northward thinning and eventual loss of coal is attributed primarily to differential erosion of peat by fluvial channels, which are inferred to have re-established themselves, after peat accumulation, along a preferred path (Fig. 41).

Limited paleocurrent information presently available indicates that during deposition of Members 4 to 6, flow was approximately to the southeast. Fig. 42 illustrates probable basin configuration

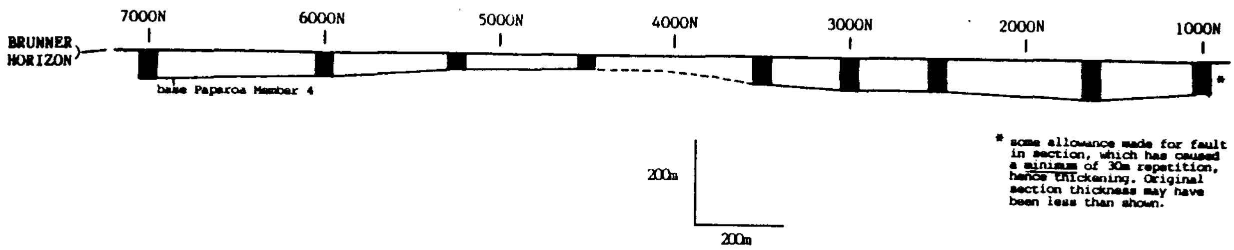


FIGURE 39. Cross section through Pike River Coalfield from north to south, demonstrating variations in the combined thickness of Members 4 to 6 of the Paparoa Coal Measures. Thinning in the central area is attributed to relatively slow subsidence at the time of sedimentation.

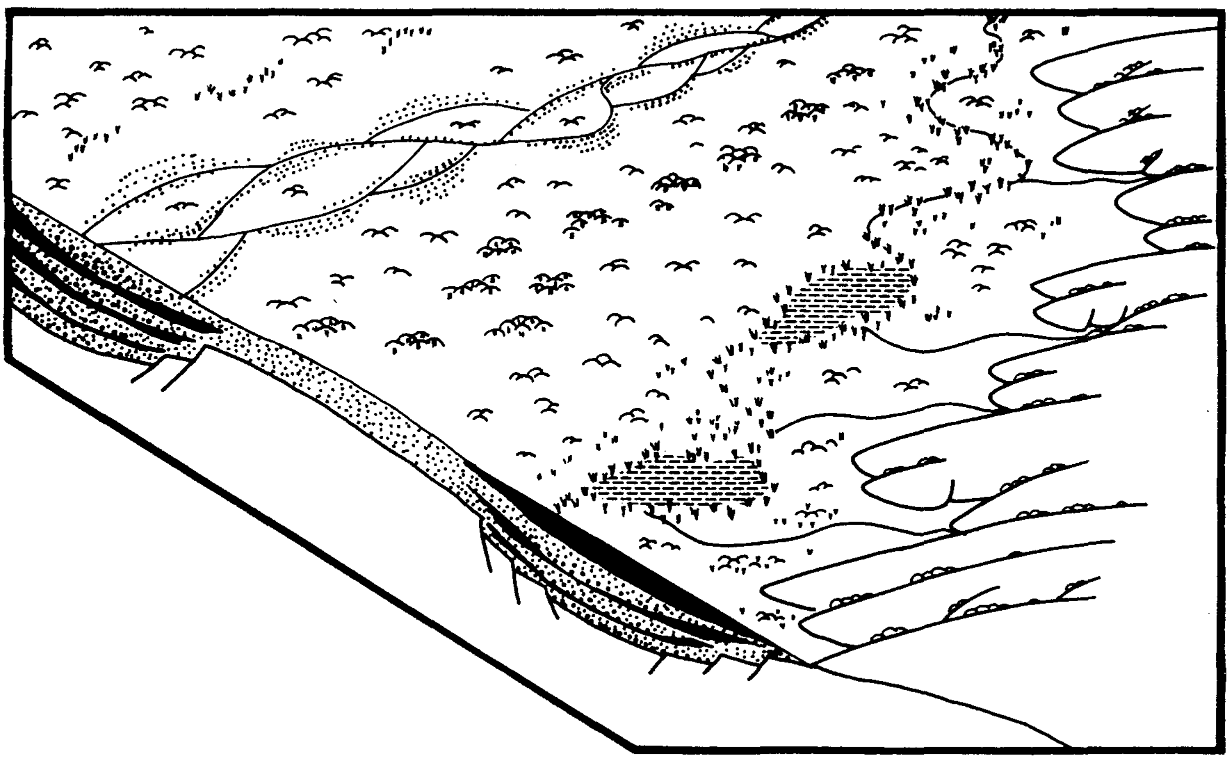


FIGURE 40. Diagram illustrating a conceptual model hypothesising the influence of a basement high on peat accumulation at Pike River Coalfield. View is to the west. Paleoflow appears likely to have been to the southeast (bottom left).

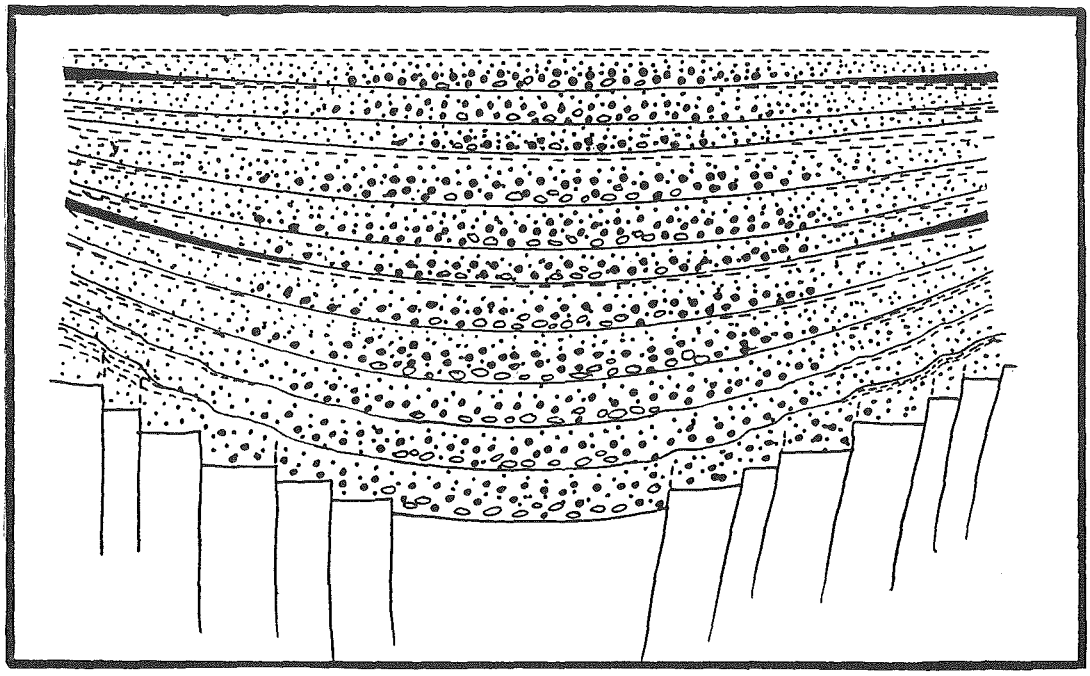


FIGURE 41.

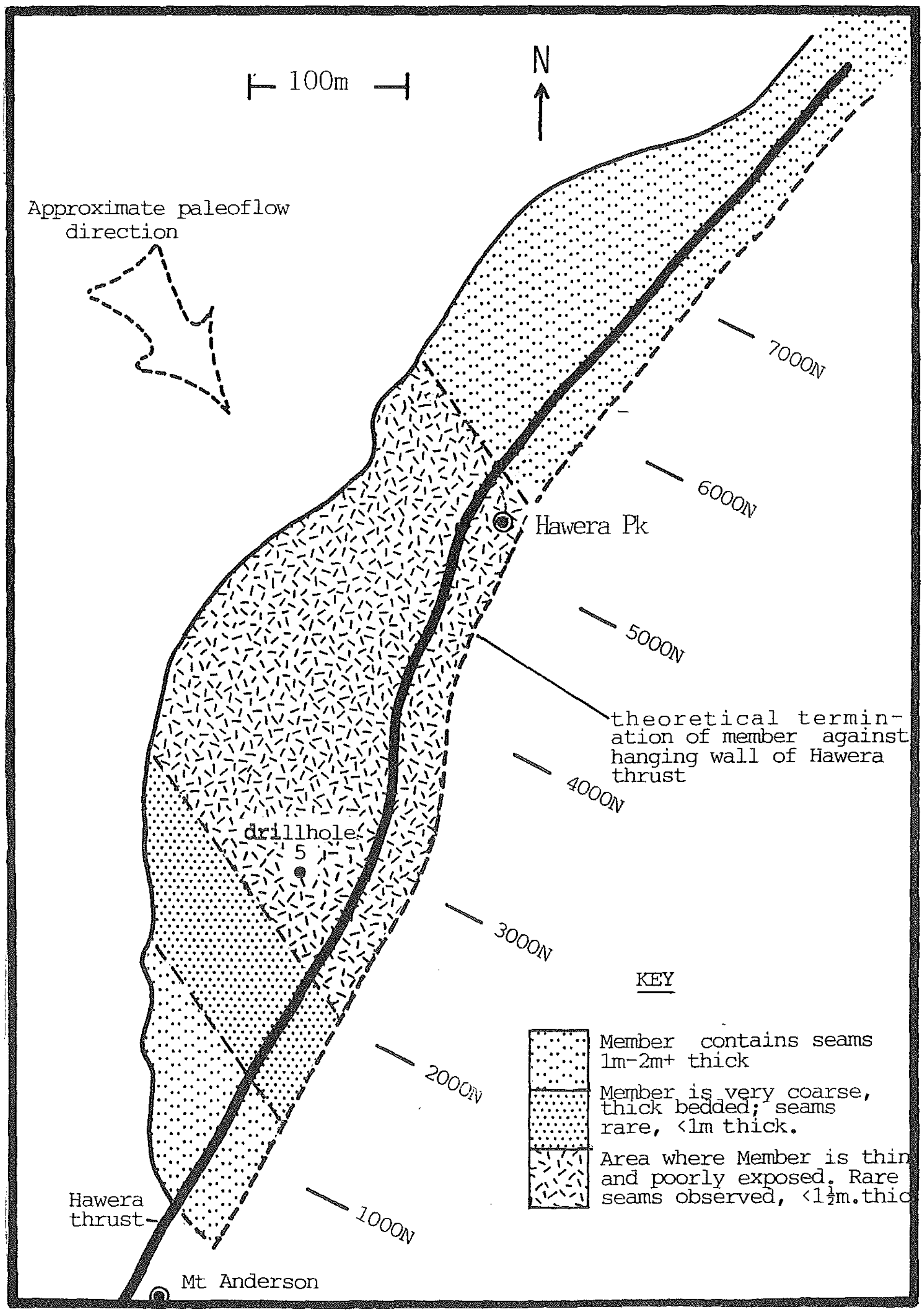


FIGURE 42.

and fluvial paleogeography during accumulation of M4, based on thickness, lithofacies and paleoflow information. According to the interpretation of Figure 42, the "barren zone" of seam washouts in M4 is likely to occupy a large area in the south of the coalfield, restricting southern workable seams to a small corner. Workable coal also occurs in the far north. The intervening zone of relatively thin coal measures is poorly exposed and virtually no information on M4 thickness, lithology and seam occurrence is available. Observations between 3700N and 3900N suggest that M6 closely overlies basement and that Members 4 and 5 may be very thin or absent.

3.3.7 Paparoa Member 5

M5 is distinguished from M4 by a relative paucity of conglomerate and granular sandstones, thinner bedding, and a generally much higher proportion of siltstone and mudstone (Fig. 43). The transition between Members 4 and 5 is gradational and coal seams locally occur near the base of M5 but never at the top. Sandstones of M5 exhibit a wider

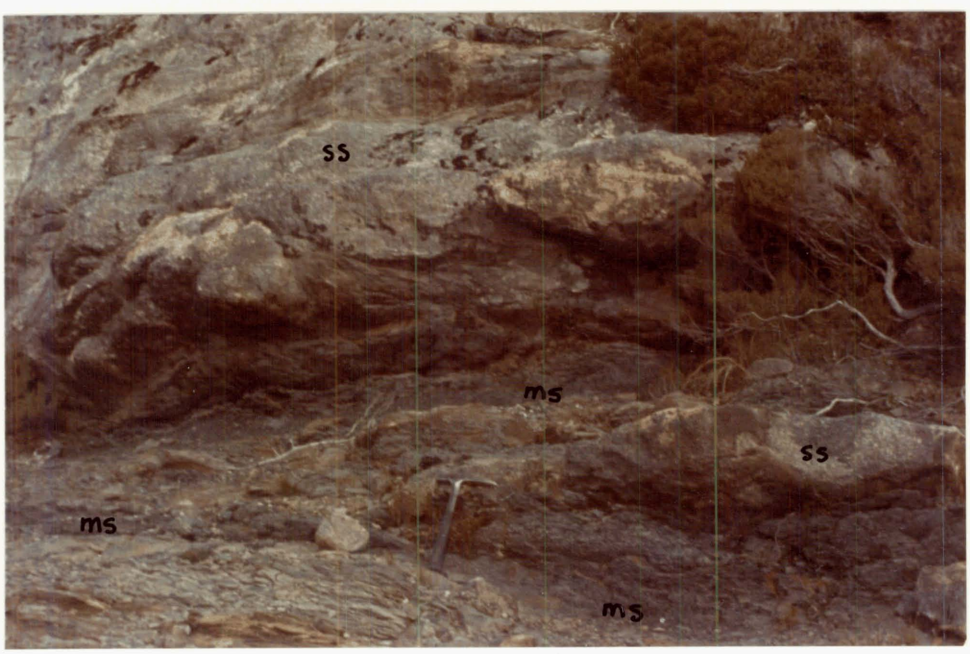


FIGURE 43. Paparoa Member 5 at 7300N, Pike River Coalfield, showing the abundant mudstone and reddish-brown colouration which characterise the Member.
mudstone = ms   sandstone = ss

variety of sedimentary structures than those of M4, but trough cross bedding remains dominant, in sets up to c. 0.5m thick. Planar cross beds in sets up to 0.3m thick and a few metres in extent have been observed very rarely. A possible example of laterally discontinuous "epsilon" cross bedding (Allen 1963) has been observed at a distance, in bluffs at 1900N.

The lateral facies changes which have been discussed in general terms for Members 4 to 6 (see 3.3.5) are well defined in M5, which tends to contain substantially finer sediments than M4 except in the channel facies area (2500N) where the Members are almost indistinguishable. The relatively finer texture in M5 probably results from a decline in current energy, perhaps in response to a reduction in paleoslope resulting from aggradation as the Goldlight lake transgressed northward in the Greymouth area. The absence of coal in M5 is considered to be primarily due to frequent flooding of vegetated areas, resulting in the accumulation of carbonaceous mudstone instead of peat. Such flooding implies failure of the mechanism hypothesised for M4, whereby fluvial activity was diverted away from potential swamps for long periods of time, due to the intervention of a zone of relatively slow subsidence between two more rapidly subsiding areas. A reduced differential between rates of subsidence in different parts of the basin is the most probable explanation for more frequent flooding and a consequent reduction in peat accumulation in M5.

Facies changes observed in the well-exposed southern area (see 3.3.5) indicate that major channels usually maintained a consistent path, with the result that areas away from this channel zone could accumulate several metres of siltstone between major floods. The coarse facies sedimentology is suggestive of an essentially braided regime, but limited meandering of some channels may have occurred within the constraints of the system.

3.3.8 Paparoa Member 6

Member 6 is a distinctive interval of thick bedded (2 - 3m+) coarse to very coarse sandstones with minor mudstone. Coal is absent, although the sandstones are frequently carbonaceous. The beds weather distinctively pale grey (Fig. 44), in contrast to relatively reddish

FIGURE 44. Paparoa Member 6 at 7300N, Pike River Coalfield, showing the grey very coarse sandstone lithology which characterises the Member. Each bed is approximately 2m thick.

FIGURE 45. Contact between Paparoa Members 5 and 6 at c. 3000N, Pike River Coalfield. The arrow marks an abrupt transition from lenticular bedded sandstones (with interbedded mudstones) of Member 5 upwards to relatively pale and tabular bedded sandstones (with minor mudstone) of Member 6.

c. 1m

underlying members. Feldspar is less abundant and more weathered than in Members 4 and 5. Bedding generally appears more orderly than in M5 because successive beds in a section are often of similar thickness and texture and appear more continuous laterally (although the latter is difficult to establish due to discontinuous exposure). Sedimentary structures are usually difficult to detect in M6 sandstones. Parallel lamination and very low angle cross bedding appear to be dominant, and trough cross bedding in sets up to c. 0.5m thick is also common. Planar cross bedding has been observed very rarely, in sets less than 1m high.

The basal contact of M6 is clearly delineated in sections which exhibit an abrupt transition from M5 reddish-brown, irregular bedded sandstone, with mudstone, to the relatively even-bedded, grey, mudstone - deficient succession of M6 (Fig. 45). However, the contact is commonly gradational.

A tendency for M6 to contain compositionally more mature sandstones than M5 is considered to result from a decline in rate of subsidence, possibly associated with climatic warming, as suggested for the lithologically similar (see 3.2.1 (e)) and possibly correlative (see 2.3) Dunollie Member at Greymouth. An overall decline in mudstone abundance in M6 compared with M5 may result from repeated reworking of sediments by fluvial channels in circumstances of slow subsidence. An absence of coal and poor preservation of pollen are consistent with these interpretations.

Where well exposed, in the south, M6 undergoes facies changes as described for Members 4 to 6 in 3.3.5. In view of the relatively slow subsidence inferred for M6 accumulation, it is surprising that differential subsidence still acted to cause channel localisation. However, substantial lateral changes in facies indicate that some mechanism must have prevented free migration of channels.

A six hole drilling programme which targeted Brunner CM (4.5) penetrated up to 35m of M6, which in Drillhole 5 (Fig. 42) consists principally of mudstone, although 600m west in the escarpment at 2500N the Member comprises granular coarse sandstones. Such dramatic lithologic contrasts may reflect the coexistence of fluvial and lacustrine environments. It is possible that channel localisation may have partly resulted from the fluvial regime entering the basin via a narrow fault-controlled passage, as suggested to explain narrowing up-paleoslope of an inferred fluvial lobe in upper Rewanui sediments at Greymouth (see 3.2.2(f)). However, there is no direct evidence for such a control at Pike River Coalfield.

3.4 PALEOENVIRONMENTS OF THE BRUNNER COAL MEASURES AT PIKE RIVER COALFIELD

3.4.1 Description of the coal measures

In most exposures the Brunner CM consist of a single, thick ($3\frac{1}{2}$ - $13\frac{1}{2}$m) coal seam (Fig. 46) directly overlain by Island Sandstone and underlain by Paparoa M6 grits, from which the seam is locally separated by thin (1 - 2m), highly quartzose and well cemented sandstone, siltstone and conglomerate (Fig. 47). The roof of the seam is intensely

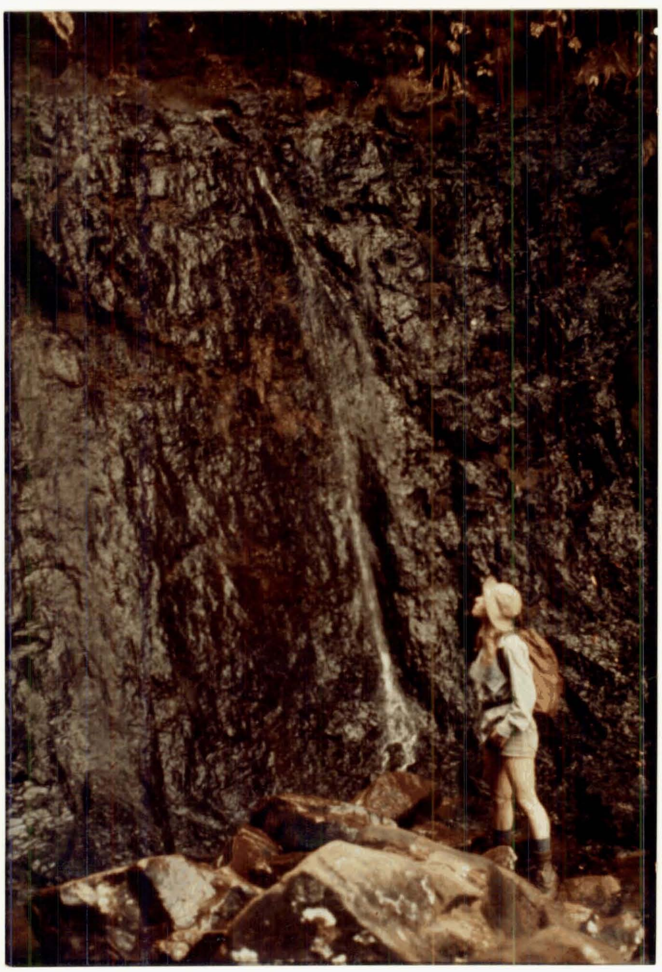


FIGURE 46. Brunner coal seam at 6500N, Pike River Coalfield. Seam thickness 9m. Roof lithology Island Sandstone (at top of frame).

FIGURE 47. Approximately 2m thick, highly quartzose interval below Brunner Seam at 7300N, Pike River Coalfield. Base of Brunner Coal Measures is at the hammer, where thin quartz conglomerate (Brunner) overlies quartzofeldspathic Paparoa Coal Measure granular sandstones.

burrowed at some localities. South of c. 1500N, this sequence is replaced by a succession of fine, massive or parallel laminated sandstones closely resembling the Island Sandstone, with which they appear to be conformable. The sandstones are slightly glauconitic (Appendix 5) and frequently contain platey intraclasts of coal (reworked peat), some of which are more than 25cm long. Mudstone is virtually absent from the succession. Two thin coal seams occur 1 - 2m apart in this southernmost area (Fig. 48). The seams contain multiple sandstone lenses and vary laterally both in total seam thickness and in thickness and distribution of the sandstone partings. All transitions from coal to sandstone have a knife-edge abruptness (Fig. 49). A well exposed example of a "starved" megaripple is shown in Figure 50. Most Coal Research Association (CRA) analyses indicate an unusually

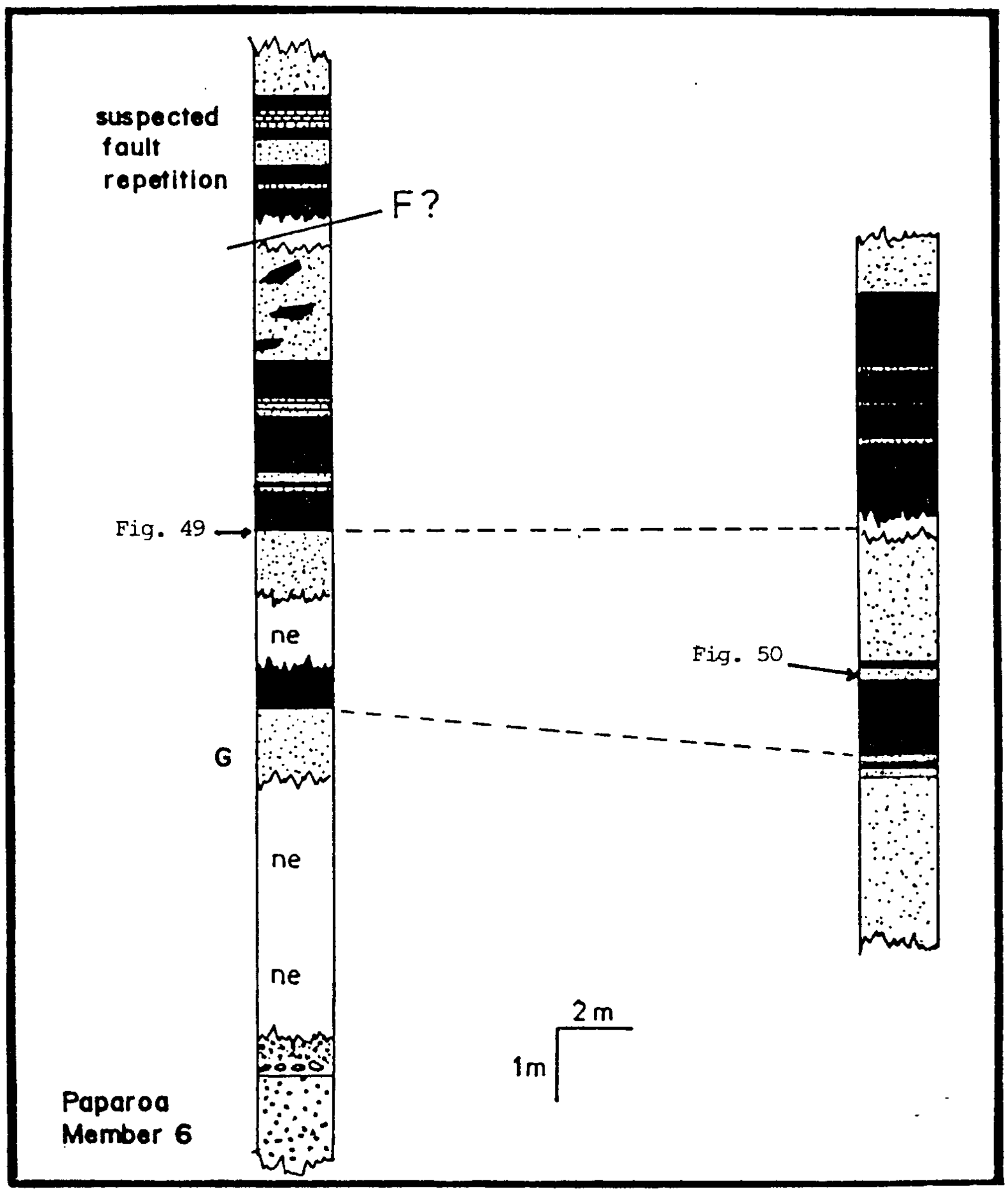


FIGURE 48. Brunner Coal Measures at Patterson's Section (c. 1300N), Pike River Coalfield. Faulting complicates the sequence and is believed to cause local seam repetition. Repeated sequences are dissimilar due to marked lateral variability in both coal and sandstone thickness, demonstrated by comparison of adjacent sections.
G = bed in which glauconite has been identified.

FIGURE 49. Detail of floor of upper seam at Patterson's Section, Pike River Coalfield (see Fig. 48). Coal/sandstone contact is knife-sharp.

high ash content (15 - 30%) compared with other Brunner coals at Pike River Coalfield. This sequence is defined as Brunner CM on the basis of the presence of coal and previous interpretations (M G Laird and S Nathan pers. comm's). However, in other respects the succession could be attributed to the Island Sandstone with equal (if not more) lithological justification.

Recent drilling in unexposed areas east of the escarpment indicates thinning and splitting of the main seam about a 1 - 6m mudstone and sandstone parting. Of six drillholes (see 4.5), only Drillhole 3 appears to have encountered a simple Island Sandstone/ unsplit Brunner seam / Paparoa M6 sequence (and even this section was complicated by reverse faulting, causing seam repetition). The sedimentary parting varies from a carbonaceous mudstone to fine to medium, frequently muddy, sandstone. Numerous simple tube burrows occur at some horizons but there is no intense bioturbation. Glauconite appears to be absent. Major differences from the exposed southern section include an abundance of mudstone and persistence of clean coal, which lacks the multiple sandstone interbeds seen

FIGURE 50. Lenticular sandstone bed exposed near top of lower seam at Patterson's Section (see Fig. 48). Bed morphology and carbonaceous laminae within the bed indicate deposition as a sandstone 'megaripple'. Coal/sandstone contacts extremely sharp.

in the south. In addition, coal intraclasts are absent from the sandstones. Drillhole 3 intersected two thick seams separated by a thin quartzose interval. The upper seam is considered to be a repetition faulted in from the southwest (Appendix 6).

3.4.2 Paleoenvironments

The coexistence of three principal paleoenvironments is deduced from available lithostratigraphic data. Sandstones with thin coal south of 1500N are inferred to have accumulated in a marine or marginal marine environment on the basis of sparse glauconite, and a general similarity of the sandstones to the overlying marine Island Sandstone. In view of the very abrupt sandstone-coal contacts, the generally high ash content of most coal samples, and the existence of a starved megaripple <u>within</u> coal, the coal seams are considered to be allochthonous, resulting from redeposition of peat derived from nearby swamps. Given the proximity of this inferred marginal marine environment to peat swamps a few hundred metres to the north, and the characteristics of the succession, a barrier bar setting appears likely.

The thick unsplit seam which dominates the Brunner succession north of 1500N is interpreted to have accumulated in extensive back-barrier swamps, which on the basis of coal type (see 4.2 and 4.5) are inferred to have been low-lying, hence extremely poorly drained, and possibly brackish.

In the area of the drillholes, peat accumulation was interrupted temporarily when an extensive body of water drowned the swamp; in view of the proximity of the southern marine environment, this water body appears likely to have been lagoonal. The resulting mudstone to muddy sandstone parting locally features short tubular burrows a few mm in diameter. An increasing proportion of sand in the parting towards the south (Fig. 51) is considered likely to have resulted from higher energy currents in the vicinity of a tidal channel connecting the lagoon with the inferred barrier bar environment represented by sandstone and reworked coal at Patterson's Section. A paleogeographic reconstruction representing all three paleoenvironments is illustrated in Figure 52.

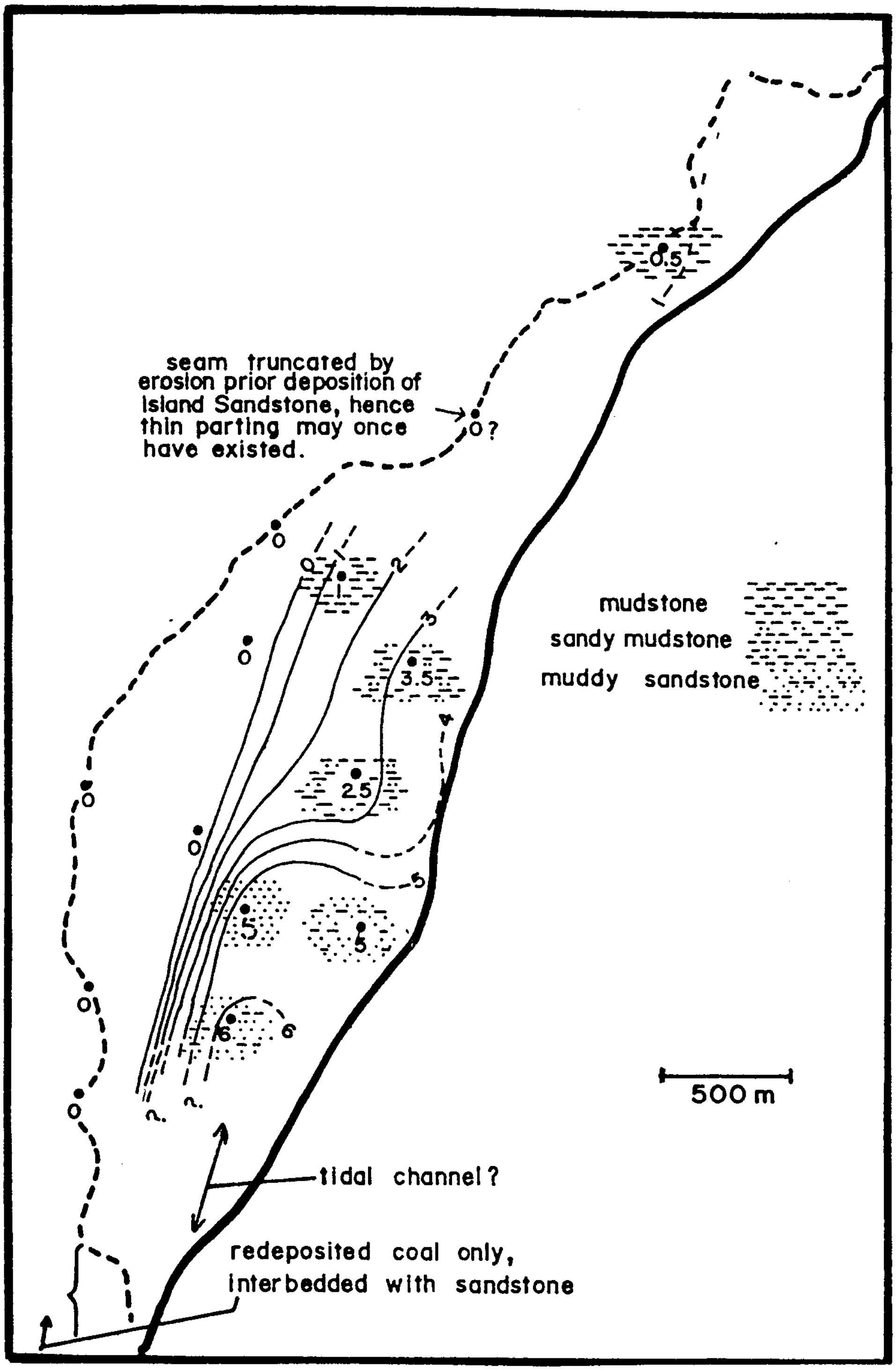


FIGURE 51. Thickness (in metres) and lithology of the sedimentary parting which splits the Brunner seam at Pike River Coalfield. The broken '5' represents the thickness and inferred original location of the parting where it is associated with the upper seam in Drillhole 3, believed to have been faulted in from the southeast. The precise relationship between the parting and the sequence at Patterson's Section (far south) is unknown.

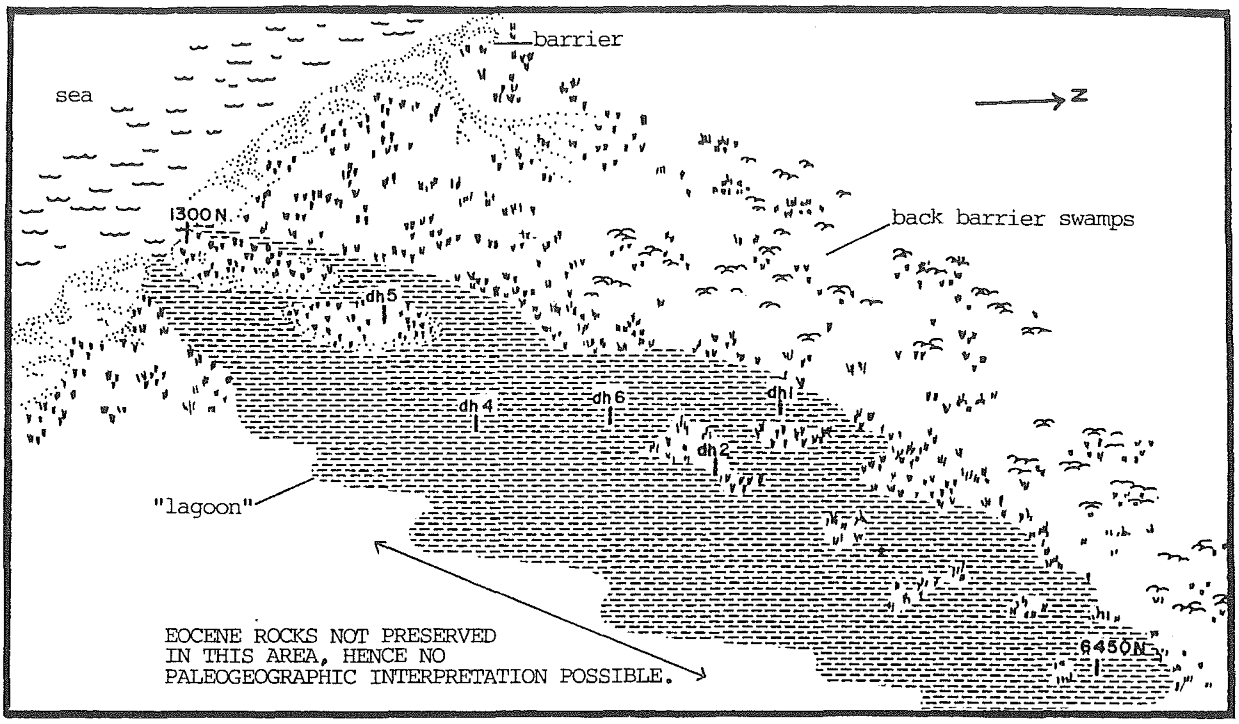


FIGURE 52. Paleogeographic reconstruction of the Pike River Coalfield during accumulation of the sedimentary parting which splits the seam in Drillholes 1 to 6. Major elements are a barrier bar in the south, back barrier swamps in the west, and an extensive drowned area, inferred to be lagoonal, in the east. Drillhole logs (Fig. 98) and locations (Fig. 97) appear in Section 4.5.

3.4.3 Tectonic controls

Paparoa CM at Pike River Coalfield (and at Greymouth) exhibit abrupt lateral changes in thickness which are attributed to syndepositional fault control in a rift basin setting. In contrast, the Brunner CM exhibit limited thickness variations in most areas, including Pike River Coalfield, and syndepositional faulting is not regarded as an important paleoenvironmental control. However, Titheridge (Newman, J. et al. 1980) invokes local fault block movements to explain patterns of peat accumulation observed at Buller Coalfield, and it is possible that the paleogeography I have inferred for Brunner CM at Pike River may reflect underlying fault control, as discussed below.

Seam thickness in the southern escarpment ranges up to 13m, and in Drillhole 5 the total Brunner sequence measures 15m, of which coal constitutes 9m. Likely correlative sediments at Patterson's Section are c. 10 - 12m thick (Fig. 48), *assuming* Island Sandstone lithologies above the coal in this section are not equivalent to Brunner coal and sandy mudstone elsewhere. If it is accepted that original peat thickness was substantially greater than present coal thickness, then using a peat:coal thickness ratio of c. 6:1, and even allowing for some syndepositional compaction and dewatering, lateral thickness variations increase substantially - from 30m at Patterson's Section to up to 80m in the escarpment. This difference may be further increased if reworked coal at Patterson's Section is interpreted to have accumulated relatively late, i.e., at the time of marine transgression, during erosion of peat in the drowned swamps. Milici (1974) suggests that barrier sandstones may accumulate on tectonically stable "shelf" zones, while lagoonal and marsh sediments accumulate in slowly subsiding adjacent sedimentary basins. Such circumstances would be consistent with Brunner CM paleogeography at Pike River Coalfield, and with inferred lateral variations in original thickness of the coal measures.

3.5 CONCLUSIONS

Basin studies conducted in varying degrees of detail at Greymouth and Pike River Coalfields indicate that Paparoa CM accumulated in fault controlled basins, which probably developed by incipient rifting during separation of New Zealand from Australia. Information provided by sediment composition suggests that Greymouth and Pike River were connected by a common rift system during much of Paparoa CM accumulation. Basin geometry was complex and basin margins abrupt, resulting in rapid lateral thickness and lithofacies changes.

Clastic sedimentation and peat accumulation are inferred to have been largely controlled by syndepositional tectonism. In particular, lateral variations in rate of subsidence appear to have stabilised the location of high-energy fluvial regimes during accumulation of the Paparoa CM. This effect permitted thick peat to accumulate in effective isolation from sediment supply despite proximity to zones of active sedimentation. By this and other means, complex tectonic activity appears to have resulted in substantially greater reserves of thick, low-ash coal than is likely to accumulate under circumstances of similarly rapid but more uniform subsidence in a relatively simple sedimentary basin. Particular examples of paleogeographic zones and coal seams which demonstrate the influence of basin development on peat accumulation are presented in Chapter 4.

The stratigraphy and seam distribution of Brunner CM at Pike River Coalfield indicate that Brunner paleogeography may also have been influenced by syndepositional faulting. However, the effects of the postulated tectonic controls manifested themselves in a very different way than in the non-marine Paparoa CM, due to the marginal marine setting of the Brunner CM.

Interpretation of tectonic history from general basin studies is inevitably somewhat speculative, given the indirect nature of relationships between available data (e.g., thickness and lithofacies variations) and actual tectonic processes. Where the data itself are limited or unreliable, due to ambiguity of geophysical logs, wide spacing between drillholes, poor exposure, and structural complications, the reliability of hypotheses relating tectonic aspects of basin development to paleogeography and sedimentation is further reduced. Consequently, most such hypotheses must be regarded as working models to be tested and refined if more data become available, or existing data are examined in greater detail and reinterpreted. Particularly worthwhile topics for further investigation include the following:

(1) location and examination of cuttings from Greymouth drillholes which were not cored and for which gamma-ray logs appear susceptible to misinterpretation;

(2) a more organised and thorough investigation of Rewanui Member sandstone petrology in the west of Greymouth Coalfield, aimed at clarifying paleogeography especially for the Upper Rewanui;

(3) more detailed collection of information to test the hypothesis that differential subsidence influenced the location of major fluvial channels; in particular, description of Rewanui sections in the extreme east of Greymouth Coalfield, and structural mapping to clarify thickness variations in the far south of Pike River Coalfield;

(4) collection of paleoflow data.

Further exploration by drilling would, of course, be very valuable.

CHAPTER 4

RELATIONSHIPS BETWEEN PALEOENVIRONMENT AND COAL PROPERTIES

4.1 INTRODUCTION

West Coast coals differ in many important respects from most bituminous coals which have been intensively studied overseas. In particular: (1) they have spectacularly high swelling and fluidity at coking coal ranks, (2) the maceral group inertinite constitutes less than 10% of most samples, and (3) their Cretaceous to Eocene age is young compared with Paleozoic to lower Mesozoic European, North American and southern hemisphere (Gondwana) bituminous coals. Other notable characteristics are generally large seam thicknesses (often 10m+), low ash content (typically <1 to 5%), generally poor lateral continuity regardless of seam thickness (500m to 2km, rarely to c. 6km), and rapid lateral rank changes resulting from lateral variability in burial depths. In addition, the coal bearing formations are themselves distinctive, being almost solely either thick, laterally restricted, and non marine (Paparoa CM), or thin, extensive, and marginal marine (Brunner CM).

Most coal properties exhibit variability which can be at least partly attributed to paleoenvironmental influences, such as swamp drainage and sedimentary regime. In the case of properties such as mineral matter content and coal macerals, this relationship is widely recognised and moderately well understood. In contrast, certain other characteristics, such as vitrinite reflectance, are assumed to be a function of rank and thus largely independent of paleoenvironment. Between these extremes lie other properties, for example volatile matter yield and hydrogen content, which are generally acknowledged to undergo variations that cannot be attributed to rank, but which are not well understood.

A major objective of research documented in this thesis is to define relationships between specific coal characteristics and the paleoenvironmental factors by which they were influenced. Therefore, an important aspect of the work has been identification of those coal properties which appear to be dependent on depositional circumstances, a task complicated by the fact that most properties are influenced by both paleoenvironment and variations in coal rank. Rank is used here in the accepted sense of thermal maturity (e.g., Stach et al. 1982, p. 67, para 2), and coals of equivalent rank are regarded as those which have been subject to the same history of temperature and pressure during burial. In practise it is difficult to be sure that coals are of the same rank unless they are plies from a common seam intersection, in which case they are referred to as serial samples and an isorank relationship is assumed. When samples are not from the same seam intersection some idea of relative rank can frequently be obtained, for example coal can be assumed to decrease in rank upwards in a section provided there is no fault repetition.

The usual practice of assessing rank on the basis of vitrinite reflectance, volatile matter, specific energy etc., is approached herein with extreme caution because investigation of serial samples has shown that all the traditional rank indicators are strongly influenced by paleoenvironment. Variations in coal properties which can be shown to result from paleoenvironmentally induced variations in the organic fraction of coal are broadly referred to as "coal type" variations. The phrase coal type is therefore not restricted to discussion of coal macerals, and it is possible to refer to a "high-volatile type" for example. Wellman (in Gage 1952) and Suggate (1959) adopted this relatively broad usage when it became apparent that New Zealand coals exhibit marked variations in chemistry which have nothing to do with rank.

Research findings in this chapter are presented in a chronological sequence of case studies, commencing with a brief outline of important early results for Paparoa and Brunner coals from the south of Pike River Coalfield. This work provided preliminary evidence that West Coast coals cannot be assumed to conform to traditional principles established overseas, particularly in the case of vitrinite reflectance, and serves to introduce fundamental themes of the research as a whole. Subsequent work (4.3 to 4.6) confirmed and progressively extended conclusions regarding relationships between paleoenvironment and coal type which were first formulated during the reconnaissance work on Pike River coals.

Methods employed in coal sample preparation and petrographic analysis appear in Appendix 7.

4.2 RECONNAISSANCE INVESTIGATION OF COALS AT PIKE RIVER COALFIELD

4.2.1 Introduction

Paparoa and Brunner coals differ principally in textural character. Brunner examples consist predominantly of extremely fine-grained clarain, which produces a homogenous appearance in hand specimen, referred to in the past as "canneloid" (e.g. Gage 1952 p. 105). Although Paparoa coals also consist predominantly of clarain, the constituent vitrinite macerals are larger and result in a more laminated or fibrous appearance. At Greymouth and Pike River Coalfields the Paparoa and Brunner coals differ chemically also, whereby Brunner coals generally have a higher volatile matter yield than Paparoa coals of similar rank (Wellman, in Gage 1952). However serial samples, particularly from Buller Coalfield (Webb/Baynes Block, see 4.6), indicate that Brunner coals can vary widely in type-related characteristics such as volatile matter yield, vitrinite reflectance, and carbonisation behaviour, and some are of low-volatile type.

Maceral analyses and reflectances of Brunner and Paparoa coals from Pike River Coalfield were first presented in a Robertson Research report (Allen et al. 1974), for which four samples were examined. Mean maximum vitrinite reflectance in oil immersion ($\overline{R}o$ max) averaged 0.67% for two Brunner samples and 0.95% for two Paparoa samples. This difference is greater than can be accounted for by the stratigraphic separation of the samples (c. 100m), even if coalification occurred in a high geothermal gradient. Consequently Allen et al. hypothesised that the Paparoa coals were buried to a considerable depth and coalified, then uplifted and uncovered prior to deposition of the overlying Brunner CM. However, this interpretation is improbable, because regional geological evidence indicates that the Paleocene was a time of tectonic quiescence throughout the West Coast (e.g., Nathan 1978).

During 1980, a reconnaissance petrological survey undertaken by the writer, using small samples obtained during initial field work at the coalfield, tentatively confirmed the reflectance data of the Robertson Research report. More detailed work was subsequently carried out on representative splits of the original channel samples, prepared by CRA.

4.2.2 Results

Representative results are presented in Figure 53, with proximate and maceral analyses in Table 1. Pike River coals are slightly anisotropic, and in this study $\overline{R}o$ max was measured. Only relatively thick telocollinite (>50µ) was used for reflectance measurement. Observation of the samples suggested that if desmocollinite and thin telocollinite had been included, $\overline{R}o$ max for most samples would have been significantly lower. Many seams have a diffuse distribution of reflectance values, with weakly defined peaks, but differences between certain seams are distinct. Figure 53 shows that although some Paparoa seams have $\overline{R}o$ max >0.90%, most have a substantially lower reflectance not noted by Robertson Research. Paparoa seams with low $\overline{R}o$ max, similar to that of the Brunner coal, occur in M3 near the base of the Paparoa CM and underlie M4 seams with much higher $\overline{R}o$ max, showing that variation of reflectance cannot be explained by varying depth of burial, as attempted by Robertson Research.

Samples examined during this preliminary work were deliberately restricted, with one exception, to Patterson's Section in the south of the coalfield (Fig. 27), where several different seams are available for study. Possible effects of lateral rank variation were thereby avoided, an advantage which outweighed the fact that most of the samples at this location are moderately weathered. The stratigraphic relationships of seams shown in Figure 53 are not seriously disturbed by faulting, and intrusive igneous rocks are absent from the succession.

4.2.3 Discussion

Moisture content, swelling number, and calorific value indicate that Brunner coal at Pike River has a similar rank to the Paparoa coals, not a much lower rank as suggested by Robertson Research, who were misled not only by low Brunner reflectances, but also by proximate analyses of weathered coal. Reflectance itself does not appear to be much affected by weathering, but in other respects it is

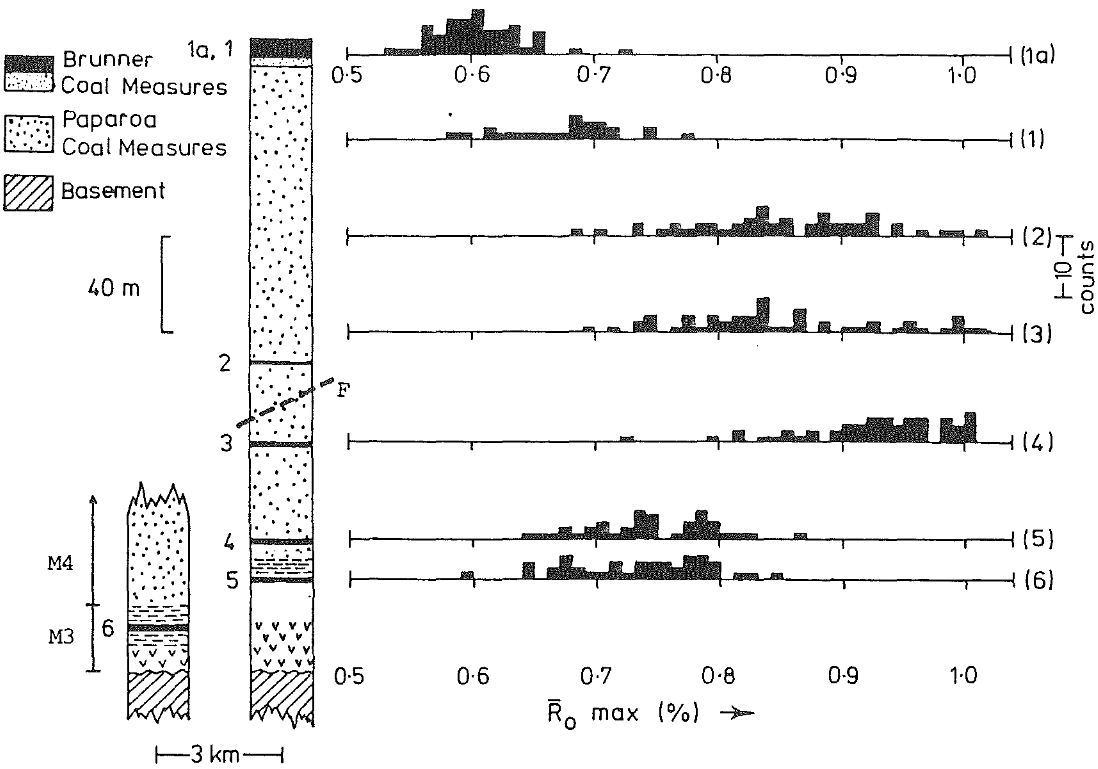


FIGURE 53. Reflectograms and stratigraphic data for 6 coal samples from Pike River Coalfield.

Table 1 Analytical data for seams shown in Fig.53 Samples are moderately to highly weathered, hence CSI and moisture values differ from those quoted in the text for the freshest Pike River coals. The data for each seam are all derived from a single sample, identified by Coal Research Association (CRA) number. Table from Newman & Newman (1982).

SEAM NUMBER	1a[1]	1	2	3	4	5	6
C.R.A. NUMBER*	27/517	27/545	27/232	27/535	27/537	27/541	27/522
moisture %	6.1	1.4	2.4	2.2	1.4	3.4	1.8
ash % (dry basis)	5.0	12.8	3.2	4.3	7.7	6.9	6.4
volatile matter % (dmmsf)[2]	44.0	40.8	35.9[3]	35.1	36.8	38.0	41.0
calorific value in B.t.u. (dmmsf)	14,090	15,748	15,307	15,261	15,537	14,893	15,237
sulphur %	1.3	4.1	0.5	0.8	0.4	0.5	0.4
C S I[4]	1	8½	2½	7	8	1½	4
R̄o max %	0.60	0.67	0.85	0.84	0.92	0.74	0.73
Telocollinite %	10.2	9.2	30.4	34.1	29.3	15.5	24.5
Desmocollinite %	68.5	71.2	58.8	50.2	57.7	67.5	59.5
Exinite %	18.8	11.6	4.6	7.2	5.0	5.0	7.1
Inertinite %	1.7	3.0	5.8	7.5	6.0	8.5	7.7
Mineral matter %	0.8	5.0	0.4	1.0	2.0	3.5	1.2

[1] 0.7m interval at top of seam
[2] Dry, mineral matter and sulphur free basis of Suggate (1959).
[3] Original value 34.5%. Adjusted as recommended by CRA to compensate for change in analytical method between this and the other analyses (Appendix 8).
[4] Crucible swelling index.
*UC Sample No. equivalent is provided in Appendix 5.

important to evaluate only analyses of the freshest samples available, which have higher calorific value, swelling and sulphur, and lower moisture than corresponding weathered coals. The freshest Pike River coals analysed in 1981, when the reconnaissance investigation concluded, average 1% moisture, 40% volatile matter (dmmsf, i.e., the dry mineral matter and sulphur free basis of Suggate 1959; see also Appendix 8), 36.5 MJ/Kg calorific value (also dmmsf, Suggate 1959), and have swelling values of 9+. On this basis the Brunner and Paparoa coals are both of high volatile bituminous A rank. Greymouth coals with similar properties (e.g., Paparoa coal at Liverpool State Mine, Suggate 1959) have $\overline{R}o$ max c. 0.90%, a reflectance in the range expected for high swelling, low moisture coals. Many Pike River coals must therefore be regarded as having abnormally low reflectance.

Hutton & Cook (1980) have shown that alginite in coal can cause depression of vitrinite reflectance, but alginite is not found in Paparoa coals at Pike River, and although it could be present as liptodetrinite (degraded exinitic debris) in the Brunner coal it is unlikely to be abundant. Anomalously low reflectance vitrinite can also result from coalification of unusually lipid-rich plant tissues (Stach et al. 1975). Such vitrinites are present in Pike River coals but they are not dominant. Additionally, the reflectance of several telocollinite "varieties" occurring in the Paparoa coals appears to follow the interseam reflectance variations previously noted, indicating that telocollinite reflectances are not directly dependent on the primary composition of precursor plant tissues.

Anaerobic peatification is known to produce unusually perhydrous (hydrogen-rich) vitrinites which have depressed reflectance (Stach et al. 1975). Such vitrinites may also fluoresce weakly under prolonged blue light irradiation (Teichmuller 1974), a phenomenon demonstrated by some Paparoa and all Brunner coals from Pike River Coalfield. In addition, vermicular clays, which occur in many Pike River coals, exhibit vivid yellow fluorescence due to impregnation by perhydrous compounds, and a green-fluorescing oil is expelled from cracks in many Pike River coals during blue light irradiation. Volatile matter and reflectance vary inversely in Pike River coals (Table 1), and this relationship is consistent with the presence of perhydrous vitrinites, although it is complicated by variation in exinite abundance.

The anomalously low reflectance Paparoa and Brunner coals from Pike River Coalfield differ petrographically (Table 1). In particular, the Brunner coals generally have lower telocollinite and inertinite and higher exinite than Paparoa M3 coals, and frequently have a finer texture. However, both groups of coals show evidence of peat accumulation under very wet conditions which would induce relatively anaerobic peatification. The Paparoa examples are from M3, in which seams up to 10m thick, but of limited extent ($\leqslant$0.5km), pass laterally into mudstone, which is also represented as dirt bands within the seams. Abundant very fine detrital sediment is often intimately mixed with coal macerals, and some plies are more strictly carbargillites than coal. Small clasts of reworked peat occur, easily detected only when their petrographic character contrasts with that of the surrounding coal (4.3.2). Vitrodetrinite and inertodetrinite (vitrinitic and inertinitic debris) are much more abundant in these lower seams than in younger Paparoa coals higher in the sequence. The above characteristics all indicate frequent peat swamp flooding, attributed to poor drainage of the swamps (also see 3.3.4). It is envisaged that peat accumulated in saturated, vegetation-choked basins where low-gradient streams wandered sluggishly and frequently overflowed their banks. Conversely, coal measure sedimentology shows that the later Paparoa seams, which have higher reflectance, accumulated within a well established and relatively large scale fluvial system (see 3.3.5 to 3.3.8). Most of these coals have sparse inertodetrinite, and mineral matter is restricted to a few horizons. The younger Paparoa swamps are, therefore, inferred to have been relatively well drained and infrequently flooded. Access of oxygen to the peat is indicated by the occurrence of fusinite and semifusinite, which appear to have formed in-situ, in contrast to the inertodetrinite introduced to M3 peats during floods.

Brunner coal at Pike River Coalfield has a characteristic finely degraded texture, dominated by desmocollinite and vitrodetrinite, with up to 20% exinite and a few percent of very low reflectance inertodetrinite. Telocollinite is often sparse. The seam has a marine roof and coal measure sedimentology indicates that peat accumulated in low-lying, marginal-marine swamps (probably in a back-barrier setting - see 3.4). The early Tertiary climate was warm (Fleming 1979).

4.2.4 Conclusions

As discussed above, Pike River Coalfield paleoenvironments and coal petrology suggest that very poor drainage of peat, with consequent restriction of oxygen, was the principal cause of low vitrinite reflectance in Brunner and Paparoa M3 coals. In addition, the Brunner swamps may have been relatively warm and brackish, which would encourage a high rate of bacterial activity in the peat. Coupled with an oxygen deficiency, these circumstances would produce extremely perhydrous vitrinites (Stach et al. 1982), especially if the vegetation was predominantly a hydrogen-rich "reed swamp" type, as indicated by depositional setting and generally sparse telocollinite. Brunner coals at Pike River, therefore, can be expected to have particularly depressed reflectance. Compared with Brunner swamps, the intermontane Paparoa swamps were probably relatively cool (Fleming 1979) and acid. Low reflectance in basal Paparoa coals at Pike River is, therefore, attributed almost solely to oxygen deficiency caused by very wet swamp conditions, possibly coupled with a cellulose-rich and/or lipid-rich flora. Underlying alkaline volcanics do not appear to have influenced Paparoa swamp chemistry by calcium enrichment and the consequent alkalinity which would result in perhydrous characteristics (Stach et al. 1982). Common indications of calcium enrichment (e.g., high organic sulphur, syngenetic pyrite, extreme degradation of plant tissues, unusual abundance of carbonates) are absent from these coals. In addition, many Paparoa coals from Greymouth and Pike River Coalfields which exhibit perhydrous properties are not associated with volcanics (4.3 & 4.4).

4.3 PAPAROA COALS AT PIKE RIVER COALFIELD

4.3.1 Introduction

Numerous seams of high quality coal occur in Members 3 and 4 of the Paparoa CM at Pike River Coalfield. Samples selected for petrographic study include 14 from M3 and 11 from M4. All were collected north of 5000N or south of 3000N because Paparoa coal has not been located in the intervening central area, which is poorly exposed. Reconnaissance petrographic study in the south of the coalfield (see 4.2) indicated that coals from M3 and M4 differ substantially due to accumulation of peat in contrasting paleoenvironments which have been outlined in Sections 3.3.4 and 3.3.6. The relatively detailed investigation documented in this section aimed to clarify important relationships between swamp conditions and coal properties, including maceral characteristics, volatile matter yield, and vitrinite reflectance.

4.3.2 Results

Sample locations, maceral analyses and vitrinite reflectances are presented with CRA analytical data in Tables 2 & 3. Despite efforts by exploration company field staff to obtain fresh coal from outcrop, most samples proved to be moderately to severely weathered. CRA data must therefore be interpreted with caution, because weathering raises moisture content while depressing calorific value and swelling number, resulting in properties which would usually be expected from a coal of lower rank. Table 4 provides analyses for the freshest Paparoa coals currently available from the coalfield. Volatile matter is routinely corrected to a dry, mineral matter and sulphur free basis (dmmsf, Appendix 8), and an additional correction is incorporated in Tables 2 & 3 for a probable reduction in volatile matter values resulting from weathering (Appendix 8).

The 25 samples studied fall into two distinct groups on the basis of volatile matter (dmmsf) and vitrinite reflectance (Fig. 54). Group I consists of all M3 and northern M4 coals, for which volatile matter averages 40% and vitrinite reflectance 0.75%. Group II consists of southern M4 coals, for which volatile matter averages 36.5% and vitrinite reflectance 0.87%. Table 5 summarises differences between M3, northern M4, and southern M4 coals, including coal seam and lithostratigraphic characteristics. Petrographic features which M3 and northern M4 coals have in common include the occurrence of "detrital" layers and reworked peat clasts. Although of variable character, detrital layers are easily identified by their complex compositional associations and a disturbed texture (Figs 55 & 56). Vitrodetrinite and inertodetrinite are typically mixed together with liptodetrinite, often in association with clastic mineral matter. Clasts of reworked peat, frequently oxidised prior to final

	Sample location		6925			c.6700		5975	5200		c.2650			1450		
	Pike River Coal Co. No.		148	149	150	131	132	122	117	116	99	66	101	85	87	88
	Coal Research Assn No.*		30/158	30/159	30/160	30/122	30/123	27/713	27/708	27/707	27/679	27/522	27/681	27/541	27/543	27/544
	Thickness of seam/ply (m)		1.70	1.40	1.40	4.64	3.48	1.85	1.21	8.69	4.56	4.60	9.80	6.20	3.10	5.05
proximate analyses	Moisture	%	1.5	1.6	1.3	2.2	2.1	1.8	2.9	2.2	1.3	1.8	2.0	3.4	2.0	6.6
	Ash	%	17.4	6.5	28.7	5.7	9.5	5.2	3.7	7.3	28.2	6.3	22.6	6.7	15.1	6.9
	Volatile matter	%	33.0	37.2	28.0	37.5	35.1	36.9	38.5	36.9	28.4	38.3	31.4	34.9	31.7	33.6
	Fixed carbon	%	48.1	54.7	42.0	54.6	53.3	56.1	54.9	53.6	42.1	53.6	44.0	55.0	51.2	52.9
	Calorific value MJ/Kg		28.35	32.59	24.64	31.62	30.68	32.75	32.59	32.05	24.47	32.25	25.86	30.79	29.25	27.66
	Calorific value Btu/lb		12190	14010	10590	13590	13190	14080	14010	13780	10520	13860	11120	13240	12570	11890
	Sulphur	%	0.29	0.37	0.24	0.46	0.52	0.47	0.46	0.33	0.38	0.44	0.37	0.50	0.20	0.27
	Crucible Swelling No.		4	8	6	4½	4	5	2	4½	6	4	2	1½	7	0
	Volatile matter dmmsf [1,2]	%	39.4	40.1	37.3§	40.6	39.2	39.5	41.6	40.7	37.5§	40.5	40.0	39.2	37.5	41.0
maceral analyses	Telocollinite	%	37	35	22	30	40	22	25	33	31	28	30	20	31	35
	Desmocollinite	%	48	50	55	59	47	60	63	54	55	58	58	66	57	55
	Liptodetrinite	%	2	3	2	3	3	3	2	4	2	2	2	2	3	2
	Sporinite	%	1	1	2	2	2	1	1	1	1	1	1	1	tr	1
	Cutinite	%	3	1	tr	tr	1	1	1	1	1	1	1	2	1	2
	Resinite	%	-	-	1	tr	-	tr	tr	tr	-	-	tr	-	-	-
	Suberinite	%	2	1	3	1	1	2	1	tr	1	3	2	1	1	1
	Semifusinite	%	5	7	12	3	4	7	5	5	7	4	4	5	4	3
	Fusinite	%	2	2	3	2	2	4	2	2	2	3	2	3	3	1
	Total vitrinite	%	85	85	77	89	87	82	88	87	86	86	88	86	88	90
	Total exinite	%	8	6	8	6	7	7	5	6	5	7	6	6	5	6
	Total inertinite	%	7	9	15	5	6	11	7	7	9	7	6	8	7	4
	Vitrinite reflectance ($\bar{R}o$ max %)		nd	nd	0.74	0.78	nd	0.72	nd	0.74	0.79	0.73	0.74	0.74	0.80	nd

TABLE 2. Coal Research Association data, maceral analyses, and vitrinite reflectance of 14 Paparoa Member 3 coal samples from Pike River Coalfield. Maceral analyses are presented on a mineral matter free basis. Locations are given in metres north of Mt Anderson. Groups of samples from a single section or seam have the uppermost sample on the left, followed by successively lower samples in stratigraphic order.

Notes: *UC Sample No. equivalent provided in Appendix 5. 1 = dmmsf basis of Suggate (1959), see Appendix 8. 2 = corrected for weathering, see Appendix 8. § = Sample very high in ash and dmmsf correction may be unreliable in consequence. For stratigraphic columns showing seam position see T. E. Bates (1983).

Sample location		7250		6925	c.6700	6075	1600	1300			950	
Pike River Coal Co. No.		160	163	146	133	128	93	78	79	81	72	75
Coal Research Association No.*		30/179	30/182	30/156	30/124	30/119	27/673	27/534	27/535	27/537	27/528	27/531
Thickness of seam/ply (m)		2.20	1.95	1.70	3.60	2.60	2.75	1.96	3.70	2.55	1.35	1.86
proximate analyses: Moisture	%	5.1	2.6	2.1	2.4	3.7	3.5	2.4	2.2	1.4	1.4	0.8
Ash	%	6.8	8.6	6.9	2.3	8.9	2.5	10.1	4.2	7.6	10.7	6.9
Volatile matter	%	34.2	34.9	36.3	38.2	35.6	34.1	31.1	33.6	34.2	31.9	37.0
Fixed carbon	%	53.9	53.9	54.7	56.1	51.8	59.9	56.4	60.0	56.8	56.0	55.3
Calorific value	MJ/Kg	28.13	30.64	31.74	32.74	29.19	31.96	30.39	32.86	32.52	31.13	33.99
	Btu/lb	12094	13173	13646	14070	12550	13740	13060	14130	13980	13380	14610
Sulphur	%	0.30	0.46	0.32	0.37	0.48	0.35	0.43	0.79	0.37	1.26	0.36
Crucible Swelling No.		0	2½	3½	4½	1	1	2½	7	8	8	9+
Volatile matter dmmsf [1,2]	%	40.2	39.2	39.8	40.8	41.2	37.1	35.2	35.7	37.0	34.8	39.4
maceral analyses: Telocollinite	%	24	24	29	25	36	34	33	40	37	33	27
Desmocollinite	%	60	57	55	61	49	55	51	47	55	55	64
Liptodetrinite	%	2	2	3	2	3	1	1	1	1	1	1
Sporinite	%	2	1	1	1	1	1	3	1	1	1	1
Cutinite	%	1	1	tr	2	tr	1	tr	1	1	1	1
Resinite	%	tr	tr	1	–	tr	1	tr	tr	tr	tr	tr
Suberinite	%	2	2	4	1	2	1	1	3	tr	1	tr
Semifusinite	%	7	11	4	6	7	5	8	5	4	5	4
Fusinite	%	2	2	3	2	2	1	3	2	1	3	2
Total vitrinite	%	84	81	84	86	85	89	84	87	92	88	91
Total exinite	%	7	6	9	6	6	5	5	6	3	4	3
Total inertinite	%	9	13	7	8	9	6	11	7	5	8	6
Vitrinite reflectance ($\bar{R}o$ max %)		0.75	0.73	0.77	0.75	0.75	0.84	0.87	0.82	0.86	0.99	0.83

TABLE 3. Coal Research Association data, maceral analyses, and vitrinite reflectance of 5 northern Paparoa Member 4 and 6 southern Paparoa Member 4 samples. Maceral analyses are presented on a mineral matter free basis. Locations are given in metres north of Mt Anderson. Groups of samples from a single section or seam have the uppermost sample on the left, followed by successively lower samples in stratigraphic order.

Notes: * UC Sample No. equivalent provided in Appendix 5. 1 = dmmsf basis of Suggate (1959), see Appendix 8. 2 = corrected for weathering, see Appendix 8. For stratigraphic columns showing seam positions see T. E. Bates (1983).

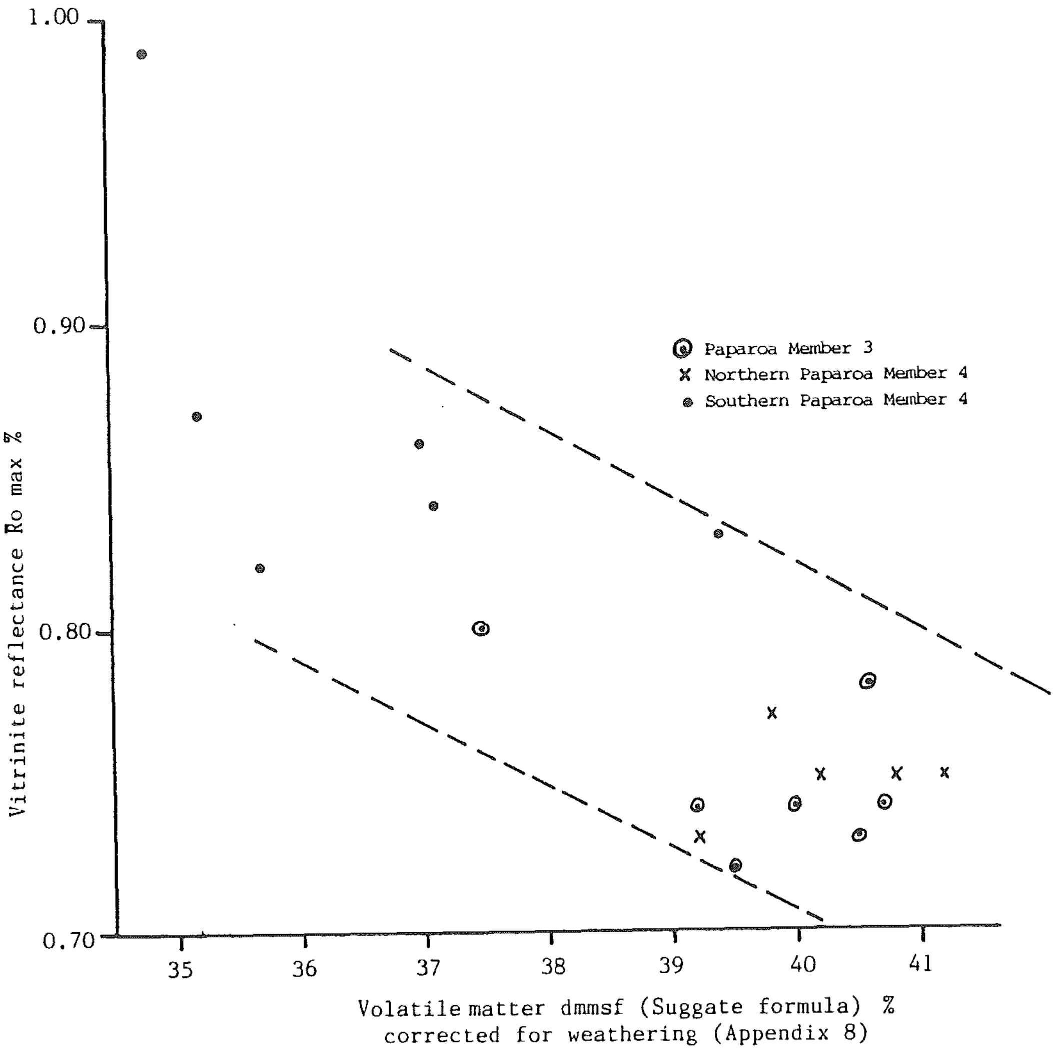


FIGURE 54. Plot of vitrinite reflectance against volatile matter for Paparoa coals from Pike River Coalfield.

deposition, commonly occur in the detrital assemblage (Figs 57 & 58). The distinctive detrital horizons can, when particularly abundant and rich in inertodetrinite, result in significant elevation of inertinite levels (e.g., samples 30/160 and 30/182). However, in many coals the horizons are volumetrically unimportant, hence cannot be detected by conventional maceral analysis. In addition, inertinite content alone is not a reliable guide to the presence of detrital layers, because it can occur in other associations. In this study the presence of detrital horizons has been established by qualitative observations of a range of textural and compositional characters.

Location		1050N	1050N
Sample Number		57	75
CRA Number		27/477	27/531
Seam Thickness (m)		1.00	1.86
Member		3	4
Proximate analyses	Moisture %	1.0	0.8
	Ash %	4.7	6.9
	Volatile matter %	38.7	37.0
	Fixed carbon %	55.6	55.3
Calorific value	MJ/Kg	34.39	33.99
	Btu/lb	14,780	14,610
Sulphur %		0.50	0.36
Crucible swelling number		9+	9+
Ultimate analyses	Carbon dasf %	nd	85.4
	Hydrogen dasf %	nd	6.0
	Nitrogen dasf %	nd	1.4
	Oxygen dasf %	nd	7.2

TABLE 4. Analyses for least weathered Paparoa coals sampled to date at Pike River Coalfield.

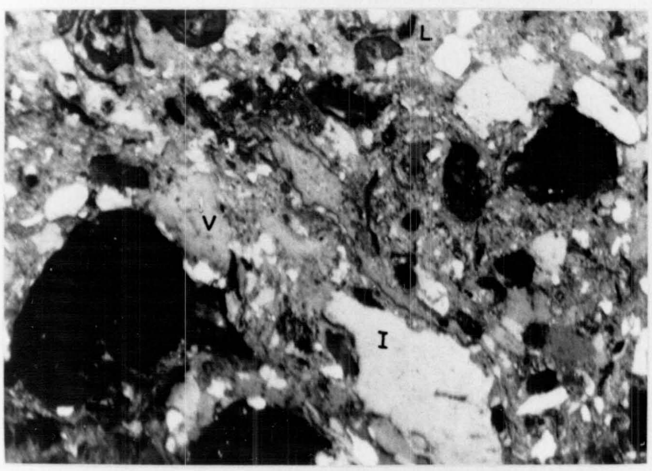


FIGURE 55.

Part of a detrital layer, exhibiting a confused assemblage of inerto-detrinite (I), vitrodetrinite (V), and liptodetrinite (L), associated with sedimentary mineral matter (black). Sample 30/160, horizontal field 0.3mm. Compare with much more featureless coal in Figure 64.

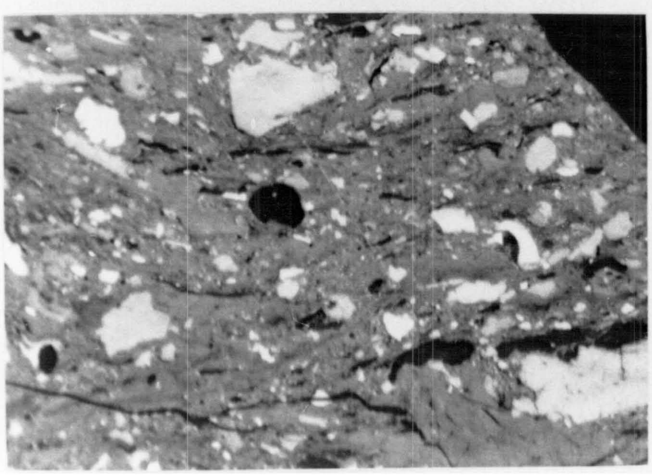


FIGURE 56.

As for Figure 55, but with relatively sparse mineral matter. Sample 27/707, horizontal field 0.3mm.

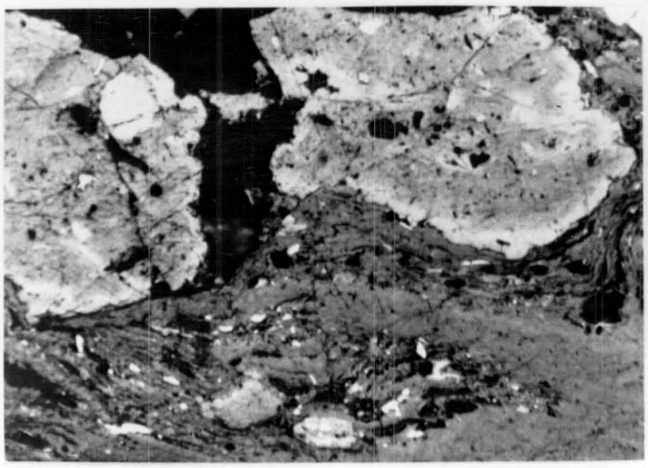


FIGURE 57.

Reworked peat clasts which suffered oxidation prior to redeposition. Reflectance is highest at the grain periphery, due to maximum oxidation at the grain surface. Sample 27/707, horizontal field 0.5mm.

FIGURE 58.

Part of a reworked peat clast which has suffered incomplete oxidation prior to redeposition. Sample 30/179, horizontal field 0.15mm.

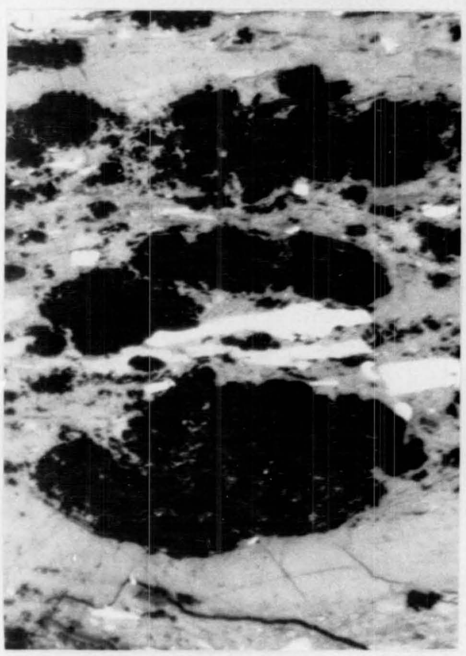


FIGURE 59.

Clay blebs in sample 30/122, horizontal field 0.2mm.

FIGURE 60.

Authigenic clay infilling cell lumens in telinite. The original cell contents which remain (top) show no sign of replacement, indicating that clay precipitated into empty cavities. Sample 30/122, horizontal field 0.1mm.

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	MEMBER 3	NORTH MEMBER 4	SOUTH MEMBER 4
average volatile matter (dmmsf basis, corrected for weathering)	40%	40%	36.5%
average R̄o max	0.75%	0.75%	0.87%
"detrital" zones	well represented	well represented	relatively sparse
reworked peat clasts	well represented	well represented	none seen
clay blebs of probable volcanic origin	well represented*	none seen	none seen
authigenic clay in telocollinite	well represented *	sparse	very sparse
seam thickness	generally >5m*	generally <4m	generally <4m
ash content	variable, sometimes >15% *	generally <10%	generally <10%
chuckies in coal	none observed	common	none observed
roof character	not scoured, over- * lain by carbonaceous mudstone	often scoured & overlain by sand- stone and grit	often scoured & overlain by sand- stone and grit
coal measure lithologies	predominantly carbon-* aceous mudstone	sandstone/grit & mudstone, minor conglomerate	sandstone/grit & minor conglomerate, sparse mudstone
volcanogenic sediments	commonly underlie * coal seams	absent	absent

TABLE 5. Comparison of Member 3, northern Member 4, and southern Member 4 coals and associated sediments. Asterixed* features are useful for differentiating Member 3 and northern Member 4 coals, which are otherwise similar in character.

Distinctive clay blebs (Fig. 59) are a petrographic feature exclusive to M3 coals. The blebs, which range in size from <0.1 - c. 0.5mm, are often composed of vermicular kaolinite, and are commonly observed in zones which are otherwise free of mineral matter. M3 coals also frequently exhibit infilling of sclerotia, miospores and cells by authigenic clays (Figs 60, 61 & 62), which is a rare phenomenon in M4 coals. M3 and M4 seams also differ in thickness, ash content, roof character and associated coal measure lithologies, as outlined in Table 5. "Chuckies" (pebbles of various lithologies) commonly occur in northern M4 seams and have not been observed in M3 coal.

As already described, southern M4 coals differ from M3 and northern M4 coals in having higher reflectance and lower volatile matter, and relatively sparse detrital zones. In addition, inertinite

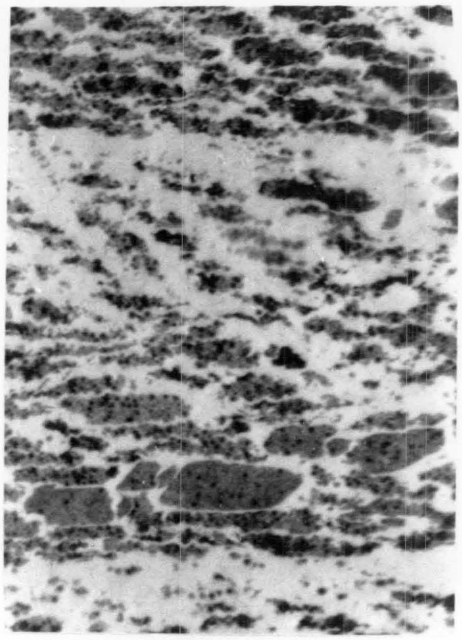


FIGURE 61.

Authigenic clay infilling cell cavities in telinite. Sample 30/122, horizontal field 0.2mm.

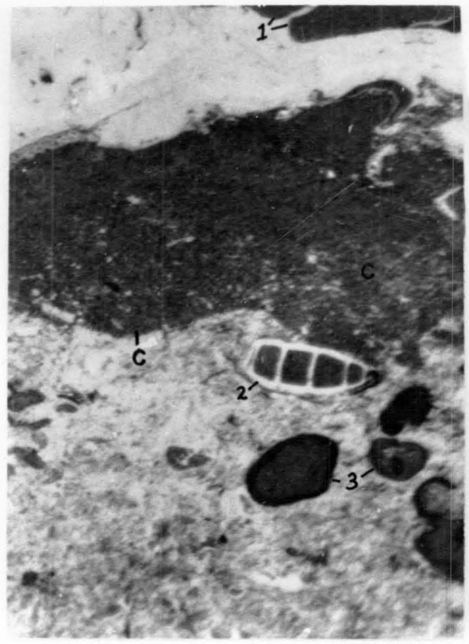


FIGURE 62.

Authigenic clay infilling
(1) cells in telinite (extreme top of field); (2) the cavities in a fungal spore (middle); (3) the interiors of plant spores or pollen (lower middle). Other clay occurrences (C) probably primary (i.e., not authigenic). Sample 30/122, horizontal field 0.1mm.

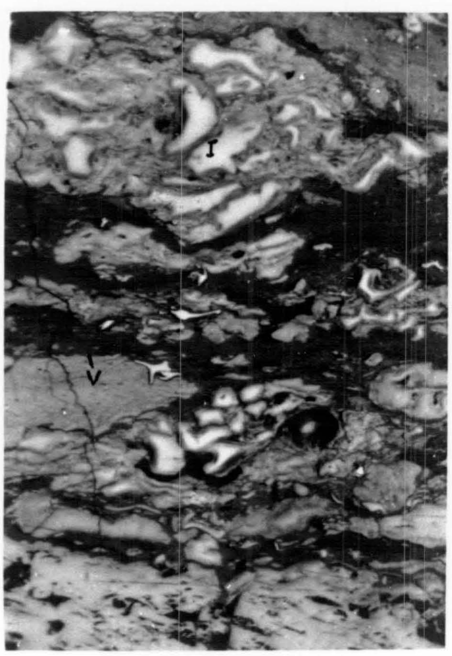


FIGURE 63.

Example of a high inertinite horizon lacking mineral matter. Inertinite (I) vitrinite (V). Sample 27/534, horizontal field 0.2mm.

FIGURE 64.

Example of the typically featureless appearance, dominated by vitrinite, of southern Paparoa Member 4 coal. Sample 27/535, horizontal field 0.2mm.

sometimes occurs within undisturbed laminae free of sedimentary impurities (Fig. 63). Chuckies and reworked peat clasts are absent. Polished sections typically exhibit large expanses of rather uniform vitrinite-rich coal, with other macerals, and mineral matter, weakly represented. This results in a relatively featureless microscopic appearance (Figure 64) compared with other Paparoa coals at Pike River Coalfield. Other seam characteristics, and associated coal measure lithologies, are similar to those for northern M4 coals.

4.3.3 Interpretation

A lack of any consistent trends in the vitrinite reflectance of M3 coals (Table 2), which are believed to be of uniform type, suggests that lateral rank changes at Pike River Coalfield are negligible. Consequently the distinction between northern and southern M4 coals on the basis of vitrinite reflectance and volatile matter is inferred to result from differences in coal type, which indicate differences in paleoenvironmental circumstances. The distinctive detrital layers of M3 coals are evidence of frequent peat swamp flooding. Flood-supplied sediments, oxidised plant detritus, and reworked peat clasts were mixed with local plant material at sites of peat accumulation. This interpretation is consistent with the relatively high volatile matter yields and depressed reflectances, properties which are attributed primarily to perhydrous vitrinite characteristics, caused by peatification in swamps with high water levels and very restricted oxygen supply (see 4.2.4). The M3 association of thick seams with frequent sediment partings and lateral gradation into contemporaneous carbonaceous mudstones (see 3.3.4) is therefore consistent with petrographic indications that peat accumulated in a poorly drained depositional regime. The apparent absence of chuckie stones, despite inferred high water levels, may result from a shortage of pebble-sized material in the vicinity. Chuckies are believed to accumulate when high stands of water permit floating trees to carry pebbles into the swamp. The distinctive, often vermicular, clay blebs which characterise M3 coals are inferred to be "kaolin-coal tonstein" material (Stach et al, 1982), and are considered likely to have a volcanic origin. Authigenic clays infilling sclerotia etc. are believed to have precipitated during peatification, from solutions containing the alteration products of unstable volcanic minerals such as plagioclase and mafic silicates.

The similarity between northern M4 coals and those of M3 in volatile matter and vitrinite reflectance, presence of detrital layers and reworked peat clasts, suggests that northern M4 swamps were also poorly drained. The presence of chuckies indicates that water levels were very high, at least part of the time. However, the M3 and northern M4 coals differ in some respects. M4 seams are usually thinner and somewhat cleaner than those in M3, and associated coal measure lithologies are relatively coarse (Table 5). In addition, M4 seam roofs are frequently scoured and overlain by coarse clastics. These differences suggest that M4 peat accumulated in relative isolation from fluvial activity (resulting in relatively low ash coals), but that episodes of swamp formation alternated with high energy fluvial activity - hence the coal measures are dominated by coarse clastics, and the seams are scoured. Peat thickness was limited by the frequency of fluvial incursion, resulting in relatively thin seams. The occurrence of high water levels in the north, despite isolation from active streams, may indicate significant ponding of drainage during periods of swamp formation, possibly as a result of the syndepositional faulting which is believed to have influenced basin development and paleogeography during M4 accumulation (see 3.3.6). The absence of clay blebs and sparseness of authigenic clays is inferred to result from cessation of volcanic activity.

Detrital zones are sparse, and chuckies have not been observed in southern M4 coals, suggesting accumulation in relatively well drained swamps which were not subject to persistent high water levels. Such conditions are consistent with a relatively low volatile matter content and higher reflectance, attributed to accumulation under more oxygenated conditions than those of the contemporaneous northern and preceding M3 swamps. Thin, high-inertinite layers lacking mineral matter probably resulted from dehydration of the peat surface. As standing water and flood waters appear to have influenced these coals much less than other Paparoa coals of the coalfield, it is possible that a moisture balance was maintained principally by rainfall.

4.4 PAPAROA COALS IN THE RAPAHOE SECTOR, GREYMOUTH COALFIELD

4.4.1 Introduction

The Rapahoe Sector is an area approximately 4km by 8km occupying the west and southwest of Greymouth Coalfield (Figs 65 & 66). Upper Rewanui seams constitute the most important reserves and are currently mined within the Sector in several private operations at 10 Mile Creek, in Strongman State Mine (9 Mile Creek), and in Moody Creek Mine (7 Mile Creek). The Rapahoe Sector has until recently been the subject of an exploration programme which commenced in 1979 and was undertaken by Lime & Marble Ltd on contract to Mines Division. Approximately 30 holes were drilled, most of which encountered seams of workable thickness and quality (Bowman 1982). All holes were geophysically logged and the Rewanui Member was usually cored. The programme was reconnaissance in nature, and drillhole spacing averages c. 1km, although in the particularly promising southwestern area a few extra holes have locally brought the spacing down to c. 500m.

Lime & Marble Ltd forwarded most seam intersections to CRA for initial preparation, splitting, and proximate, ultimate and ash constituents analysis. On instructions from Mines Division, CRA sent many sample splits to ACIRL (Australian Coal Industry Research Laboratory) for petrological analysis, washing and carbonisation tests. The resulting information on coal characteristics (Table 6) represents a considerable investment, and an opportunity for investigation of not only relationships between coal type and physico-chemical analyses, but also the value of coal properties in paleo-geographic reconstruction. To these ends, the study documented here supplements existing analytical and geological information with a relatively detailed appraisal of coal petrography and to a lesser extent, coal measure lithostratigraphy. The investigation was restricted to Upper Rewanui coals, here loosely defined as seams in the youngest one-third of the Member. Consequently, thin Rewanui sediments in the southwest are included in their entirety, despite the fact that they rest on basement, because they are considered to result from progressive southwestern onlap and to be contemporaneous with Upper Rewanui strata elsewhere in the basin.

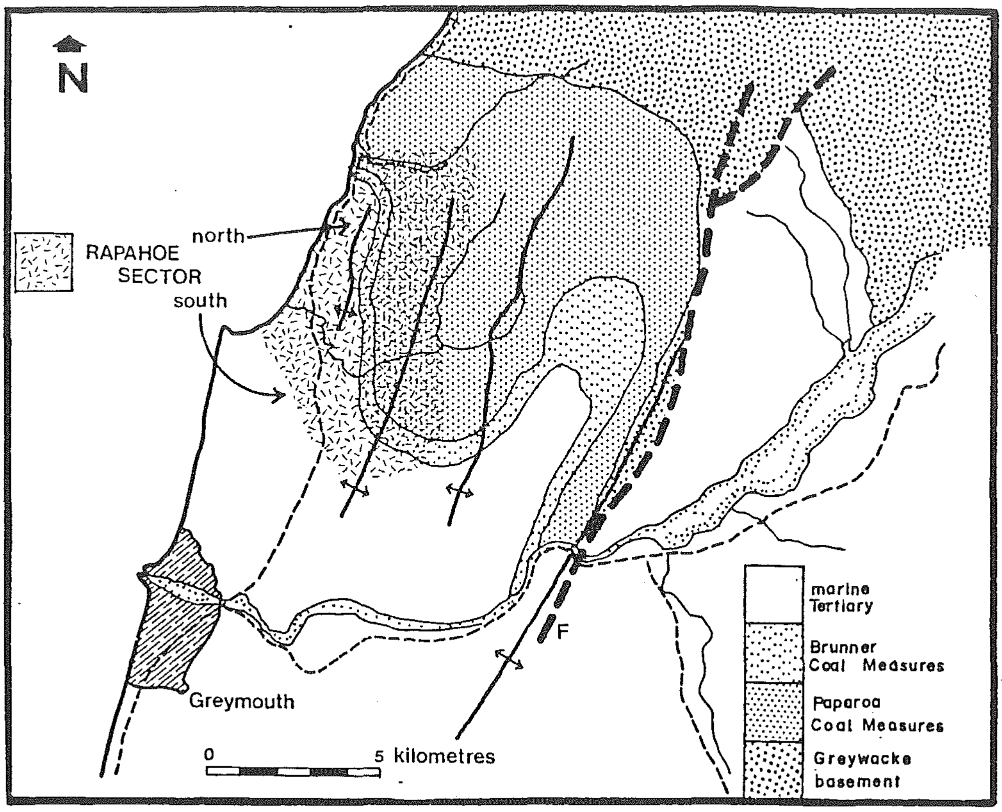
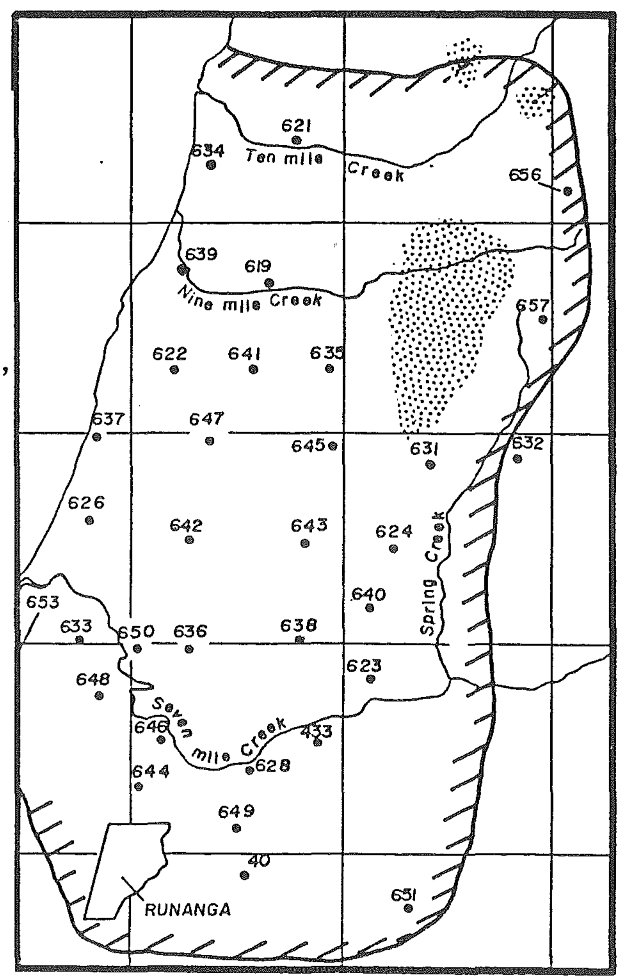


FIGURE 65. Simplified geological map of the Greymouth Coalfield showing the location of the Rapahoe Sector.

FIGURE 66. Detail of the Rapahoe Sector showing recent drillholes (and early Drillhole 40). Mined areas from which analytical data are used in this report are stippled. The outline of the Rapahoe Sector is hatched, and the map grid interval is 2km.



Drillhole	619	622	623	623	624	628	631	631	632	632	633	635	636	638	638
Seam	5	4	4	3	4	1	6	4	6	5	1	5	3	4-all plies	middle plies
CRA No.[1]	26/069*	26/186	26/267	26/263	26/298	26/376*	26/595	26/565	26/646	26/645	26/662*	26/695	26/860*	29/668	29/664*
Seam thickness (m)	1.2	5.0	1.2	1.7	2.8	10.65	8.4	9.2	1.5	1.6	10.3	3.7	12.1	18.0	11.3
Metres below top of Rewanui	c.20	c.15	0	c.43	46	13 or 36#	30	75	15	41	12	20	5	45	45
Proximate Analyses Air-dried															
Moisture %	8.4	8.5	4.9	5.7	6.4	9.9	5.4	4.6	4.3	3.7	9.3	6.2	9.1	6.9	8.4
Ash %	1.5	15.1	10.1	5.2	3.3	3.2	2.0	3.9	3.5	3.7	5.8	7.5	8.5	18.9	2.7
Volatile Matter %	39.0	33.5	36.8	37.3	38.0	37.2	40.2	40.2	39.7	39.7	41.8	38.6	35.9	33.0	38.4
Fixed carbon %	51.1	42.9	48.2	51.8	52.3	49.7	52.4	51.3	52.5	52.9	43.1	47.7	46.5	41.2	50.5
Calorific value MJ/Kg	29.96	24.57	27.97	30.49	30.57	29.14	31.59	30.97	31.47	31.64	28.2	27.76	26.95	24.52	29.70
Calorific value Btu/lb	12880	10563	12012	13108	13143	12530	13581	13315	13530	13600	12120	11935	11586	10542	12769
Sulphur %	0.58	0.78	0.49	0.36	0.30	0.29	0.26	0.30	0.31	0.32	0.59	0.94	0.23	0.22	0.24
Crucible swelling index	1½	½	1½	2½	2½	1	3	3	4½	3½	1	1	1½	1	1
dmm½sf basis Volatile matter %	44.9**	44.7** §	42.0§	41.0	41.3	42.4	43.1	43.2	41.8	41.8	48.8	43.0§	45.7§	no data	42.5
ACIRL VITRINITE REFLECTANCES AND MACERAL ANALYSES															
Vitrinite %	85	85	79	88	87	79	85	81	85	85	84	79	86		85
Resinite %	3	9	1	2	3	1	2	2	tr	2	2	4	2		3
Sporinite %	1	1	3	2	3	4	4	4	4	1	5	3	3		1
Cutinite %	1	tr	tr	tr	1	-	1	1	1	2	2	1	1		1
Fusinite %	-	-	3	1	tr	2	2	3	1	1	tr	tr	1		2
Semifusinite %	4	1	7	2	3	7	3	4	6	5	1	3	3		5
Macrinite %	-	-	tr	-	-	-	tr	tr	tr	tr	-	tr	tr		-
Sclerotinite %	-	-	-	tr	-	tr	tr	-	-	-	-	-	-		-
Micrinite %	1	tr	1	tr	tr	tr	-	1	-	tr	-	tr	tr		-
Inertodetrinite %	3	1	3	2	1	3	1	2	tr	2	2	1	2		3
Mineral matter %	2	3	3	3	2	4	2	2	3	2	4	9	2		-
Total vitrinite %	85	85	79	88	87	79	85	81	85	85	84	79	86		85
Total exinite %	5	10	4	4	7	5	7	7	5	5	9	8	6		5
Total inertinite %	8	2	14	5	4	12	6	10	7	8	3	4	6		10
$\overline{Ro}$ max (A & B) %	0.53	0.43	0.60	0.60	0.63	0.54	0.62	0.65	0.70	0.70	0.38	0.63	0.55		?
Type category assigned (I to IV)	I	?I	?IV	?II	?II	II	?I	?I	?I	?I	III	?I	III		II
Volatile matter - type	N	N	L	L	L	L	c.N	c.N	c.N	c.N	HH	c.N	c.N		L

TABLE 6. Seam location, stratigraphic position, thickness, some physical and chemical analyses, maceral analyses, and vitrinite reflectance, for selected upper Rewanui coals from the Rapahoe Sector, Greymouth Coalfield. Type categories are assigned on the basis of petrography and volatile matter yield. Samples not personally examined by the writer are assigned a tentative type number only. Volatile matter 'type' is based on Figure 70. H = volatile matter high for rank, N = 'normal', L = low, see p. 111.

* polished sample examined by writer
** adjusted to compensate for change to British Standard (Appendix 8) since samples analysed
\# depending on interpretation of position of Rewanui-Goldlight contact.
1 UC Sample No. equivalents appear in Appendix 5
2 see Appendix 8.

SOURCES

Proximate analyses, sulphur, specific energy, and swelling number are CRA results. ACIRL proximates are avoided because moisture values tend to be low compared with CRA measurements. However, volatile matter values corrected to dmm½sf (Appendix 8) depend on ash constituents data, and in cases where only ACIRL ash constituents are available (marked §) ACIRL data is exclusively used in the calculation (although not appearing in the Table). ACIRL measurements are made on washed composites, and are consequently less representative of the total sample than CRA results, however in virtually all cases >90% of the sample was retained in the floats.
Maceral analyses and vitrinite reflectance data (vitrinite A & B) are ACIRL results.

		639	639	640	640	640	641	641	643	643	644	644¶	645	646	646
Seam		2	1	8	7	6	3	2	4	3	1 (top)	1 (bottom)	6	2	1
CRA No.[1]		29/156*	29/153	29/140*	29/132*	29/117*	29/213*	29/220*	29/001	26/995	29/016*	29/075*	29/061	29/033*	29/026*
Seam thickness (m)		2.7	9.2	4.1	6.2	4.6	3.7	7.5	4.3	5.2	2.6	4.3	5.7	c.5	c.11
Metres below top of Rewanui		90	95	3	36	46	14	25	0	32	38	41	c. 30	4	31
Proximate Analyses Air-dried: Moisture	%	8.4	8.9	5.1	6.3	5.6	6.8	6.3	8.4	8.0	8.9	5.2	8.7	9.2	9.3
Ash	%	5.4	12.4	31.4	15.8	26.7	4.0	4.9	4.7	8.1	7.7	5.6	7.1	3.4	1.7
Volatile Matter	%	39.3	36.6	29.5	34.5	30.9	39.2	39.8	39.0	37.7	38.2	39.6	37.7	39.4	40.5
Fixed carbon	%	46.9	42.1	34.0	43.4	36.8	50.0	49.0	47.9	46.2	45.2	49.6	46.5	48.0	48.5
Calorific value	MJ/Kg	27.99	25.63	20.00	25.85	22.53	28.99	29.17	28.63	27.98	27.67	30.14	27.83	28.46	29.69
	Btu/lb	12034	11019	8598	11114	9686	12463	12541	12309	12029	11896	12958	11965	12230	12760
Sulphur	%	0.47	0.51	0.20	0.25	0.21	1.34	0.67	0.26	0.30	0.37	0.36	0.70	0.26	0.35
Crucible swelling index		½	½	½	1½	1½	1	1	1	2	1	1	1	1	1½
dmm ½sf basis Volatile matter	%	no data	39.9§	no data	no data	no data	no data	no data	43.8	45.3§	45.8§	44.0§	45.2§	44.4	45.4
ACIRL VITRINITE REFLECTANCES AND MACERAL ANALYSES: Vitrinite	%	71	70				76	68	80	86	79	78	85	79	82
Resinite	%	10	11				7	8	2	1	2	7	3	3	2
Sporinite	%	11	9				7	12	6	4	7	12	3	6	5
Cutinite	%	1	2				tr	1	1	2	2	1	2	1	4
Fusinite	%	tr	tr				2	2	1	1	1	-	1	tr	1
Semifusinite	%	1	1				3	1	5	2	6	1	2	5	3
Macrinite	%	1	tr				1	1	tr	-	-	-	1	tr	1
Sclerotinite	%	-	-				-	-	tr	-	-	-	-	-	-
Micrinite	%	tr	1				tr	2	tr	1	-	-	-	1	tr
Inertodetrinite	%	2	1				3	2	1	1	2	tr	tr	2	2
Mineral matter	%	3	5				1	3	4	2	1	1	3	3	tr
Total vitrinite	%	71	70				76	68	80	86	79	78	85	79	82
Total exinite	%	22	22				14	21	9	7	11	20	8	10	11
Total inertinite	%	4	3				9	8	7	5	9	1	4	11	7
$\bar{R}$o max (A & B)	%	0.54	0.55				0.63	0.64	0.51	0.51	0.52	0.53	0.59	0.47	0.46
Type category assigned (I to IV)		I	?I	IV	II + (I)	II + (I)	I	I	?I	?I	III	I & II		III	III
Volatile matter - type			LL (error in analysis ?)						L	N	N	slightly L	N	slightly L	N

¶ ACIRL data, washed sample, only 17% retained in floats.

TABLE 6 Continued.

Drillhole	647	647	648	648	649	650	653	656	656	656	657	657	Strongman Mine coal
Seam	4	2	2	1	2	1	1	5	4	3	1	2	R.O.M.
CRA No.[1]	29/711*	29/685	29/235*	29/230*	29/721	29/245*	29/738	29/755	29/754	29/753	31/729	31/735	21/703
Seam thickness (m)	12.0	10.2	2.6	5.2	2.7	3.9	3.5	1.35	2.4	4.0	6.85	6.60	"As received"
Metres below top of Rewanui	20	60	4	14	8	30	1	17+	48+	53+			
Proximate Analyses Air-dried: Moisture %	9.5	7.7	11.4	9.8	8.9	6.7	7.2	4.5	4.7	4.3	5.3	2.9	10.4 (6.2 air dried)
Ash %	6.1	2.9	3.6	4.5	5.5	8.8	21.4	9.1	5.9	3.6	5.7	2.9	4.4
Volatile Matter %	37.0	38.3	37.4	37.0	37.5	39.7	31.3	38.2	37.4	38.9	38.2	42.0	35.4
Fixed carbon %	47.0	51.1	47.6	48.7	48.1	44.8	40.1	48.2	52.0	53.2	50.8	52.2	49.8
Calorific value MJ/Kg	27.35	29.32	26.99	27.98	28.17	27.26	22.80	28.78	30.63	31.57	29.73	33.16	28.53
Calorific value Btu/lb	11758	12605	11600	12030	12111	11720	9802	12373	13169	13573	12781	14256	12270
Sulphur %	1.74	0.52	0.34	0.42	0.30	2.86py	0.62	0.29	0.24	0.21	0.22	0.29	0.27
Crucible swelling index	1	1	½	1	1	1	0	2	2½	4	2½	4½	1½
dmm½sf basis Volatile matter %	42.7	42.4	43.1	42.9	no data	44.5§	no data	no data	41.3	41.7	41.0	44.2	no data
ACIRL VITRINITE REFLECTANCES AND MACERAL ANALYSES: Vitrinite %			85	83		83							
Resinite %			3	2		1							
Sporinite %			3	3		2							
Cutinite %			1	2		2							
Fusinite %			1	2		tr							
Semifusinite %			3	4		4							
Macrinite %			tr	tr		tr							
Sclerotinite %			tr	tr		-							
Micrinite %			-	-		-							
Inertodetrinite %			1	2		1							
Mineral matter %			3	2		7							
Total vitrinite %			85	83		83							
Total exinite %			7	7		5							
Total inertinite %			5	8		5							
R̄o max (A & B) %			0.56	0.57		0.55							
Type category assigned (I to IV)	?II+(I)	?II+(I)	II	II		III			?I	?I	?I	?I (-III?)	
Volatile matter - type	L	L	L	L		slightly L			c.N	c.N	c.N	H	

TABLE 6 Continued.

Detailed sedimentary columns of the Rewanui Member in many drillholes were prepared in draft form at a scale of 1cm:2m, to assist the development of sedimentation and seam correlation models for the southern Rapahoe Sector. These columns were derived from Lime & Marble lithological logs for Drillholes 623, 628, 633, 636, 638, 640, 642, 643, 644, 646, 648, 649, 650 and 653. The detailed columns proved useful for consideration of lithological and coal seam relationships between drillholes, and aided the formulation of ideas. Their application to the study is too indirect to justify inclusion here as figures, however they are available on file in the Geology Department. Geophysical logs were also consulted, principally to check for conflicts between their data and evolving sedimentation models, particularly with respect to definition of the probably diachronous relationship between the Rewanui and Goldlight Members.

The wide spacing of the drillholes, in circumstances of coal seam lenticularity and lithostratigraphic complexity, imposes severe constraints on interpretation. Consequently only a reconnaissance study has been attempted, and specific conclusions with respect to seam correlation and paleogeographic reconstruction remain hypothetical in the absence of more detailed data coverage.

4.4.2 Variations in rank and type deduced from proximate analysis and vitrinite reflectance

Although coal type is conventionally regarded as the composition of coal in terms of maceral characteristics, certain physical and chemical properties can also be shown to vary due to type differences, for example volatile matter yield, carbonisation behaviour, and sometimes vitrinite reflectance (see 4.2). Because these properties are also affected by rank, an understanding of rank variation is important if coal type variation is to be described and understood. No single coal property constitutes a completely reliable method of rank assessment, due to the influence of type, and it is desirable to consider two or more variables when assessing patterns of rank variation. Figures 67a & 67b illustrate variations in moisture (ash free) and vitrinite reflectance (determined by ACIRL) for Upper Rewanui coals in the Rapahoe Sector. The rank patterns suggested by these two variables are reasonably congruent (if reflectance

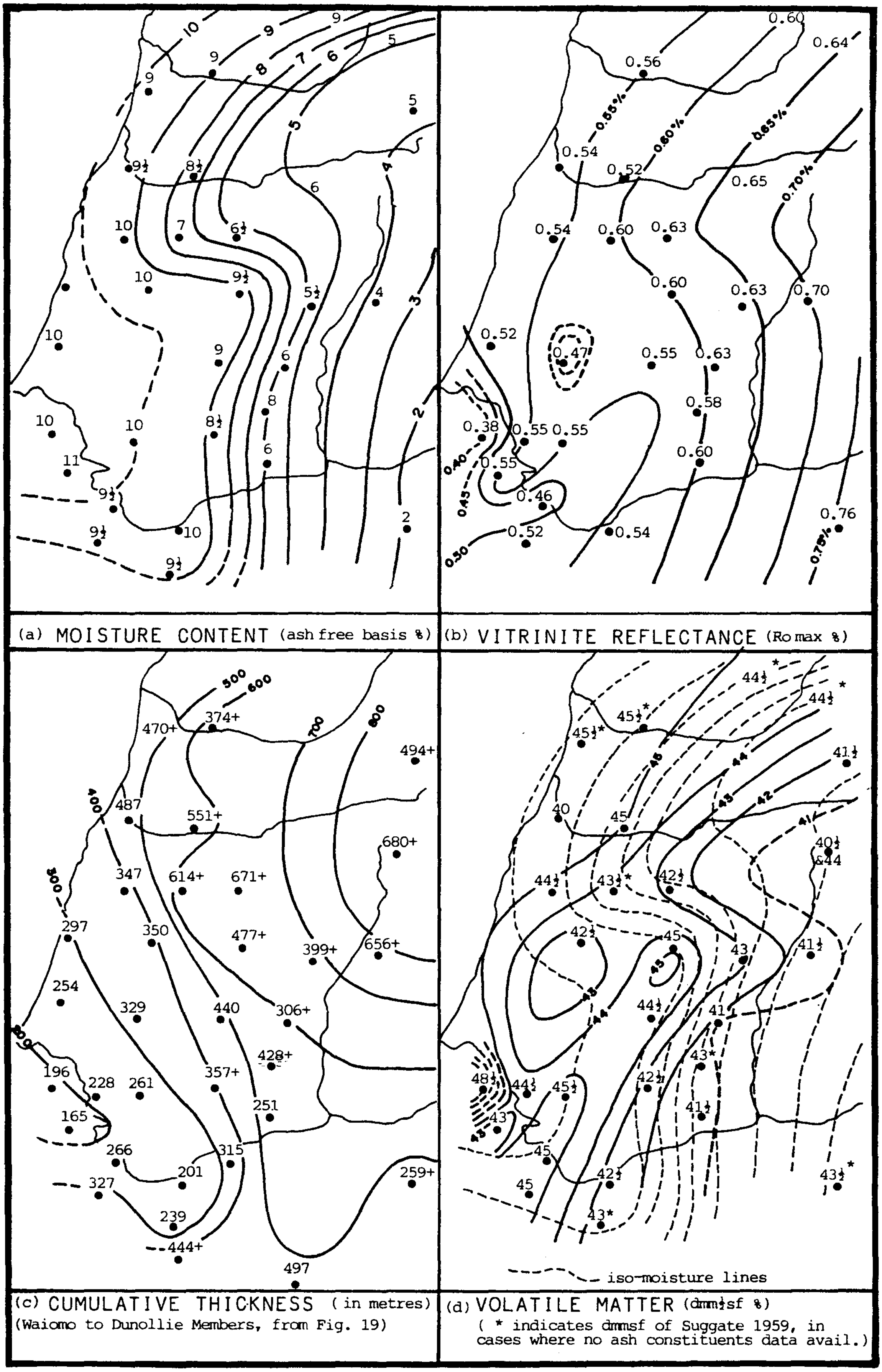


FIGURE 67. Moisture (a), vitrinite reflectance (b), and volatile matter variability (d) for upper Rewanui coals in the Rapahoe Sector. Data from Table 6 and Suggate (1959); 3 reflectance values are from Black (1980). Thickness variations for the Paparoa Coal Measures (Waiomo to Dunollie Members) are also shown (c). Map grid interval 2km.

complications in the southwest are neglected) and also broadly compatible with basin configuration (depths of burial), as far as can be determined from variations in Paparoa CM thickness (Fig. 67c).

Comparison of volatile matter trends with the inferred rank pattern provides an important indication of coal type variation in the Rapahoe Sector. If Upper Rewanui coals were of uniform type, volatile matter yield (dmm½sf, Appendix 8) would decline steadily with increasing rank. Judging from reflectance and moisture variations from west to east, volatile matter could be expected to decline approximately 5% (whether daf or dmm½sf) as a consequence of rank variation. This percentage is deduced from reflectance/volatile matter relationships in Stach et al. (1982) and moisture/volatile matter relationships in Suggate (1959). Relevant data are reproduced in Figures 68 & 69. Volatile matter values plotted in Figure 67d indicate that, although there is an overall eastward decline, this trend is disrupted by local aberrations largely resulting from lower than expected values in the southwest. These reversals in the overall trend are inferred to result from type variation. If volatile matter values are estimated for a hypothetical coal of constant type, for which rank variation is assumed to be indicated by moisture, (i.e., 4% moisture = 41% volatile matter (dmm½sf), 7% moisture = 43% volatile matter, 10% moisture = 45% volatile matter), then with reference to iso-moisture lines it is possible to designate actual volatile matter values as 'high', 'normal', and 'low' (H, N & L). Figure 70 has been annotated accordingly and illustrates, in a simplified manner, trends which can also be deduced from Figure 67d. In particular, Drillholes 623, 624, 628, 638, and 649 delineate a relatively low-volatile zone, extending westward to Drillhole 648 and 647. The absence of volatile matter data at Drillhole 642 is due to an extremely high ash content in all coals sampled. Unfortunately, no ash constituents data are available, thus reliable calculation of dmm½sf volatile matter yield is prevented. Volatile matter exhibits no overall relationship with either exinite or inertinite content (Fig. 71), suggesting that vitrinite characteristics constitute the principal coal type influence on volatile matter yield.

The patterns exhibited by volatile matter variation (Fig. 67d) broadly correspond to lateral variations in reflectance (Fig. 67b), and Figure 72 shows a plot of reflectance against volatile

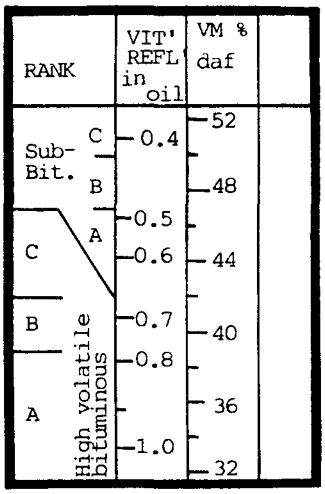


FIGURE 68. Relationship between vitrinite reflectance and volatile matter with change in rank (adapted from Stach et al. 1982, Table 4).

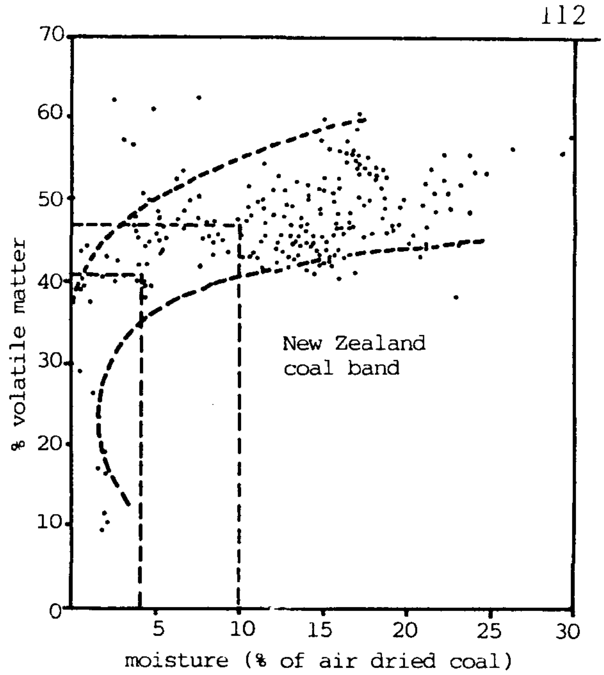


FIGURE 69. Relationship between volatile matter and moisture with change in rank (adapted from Suggate 1959, Fig. 23).

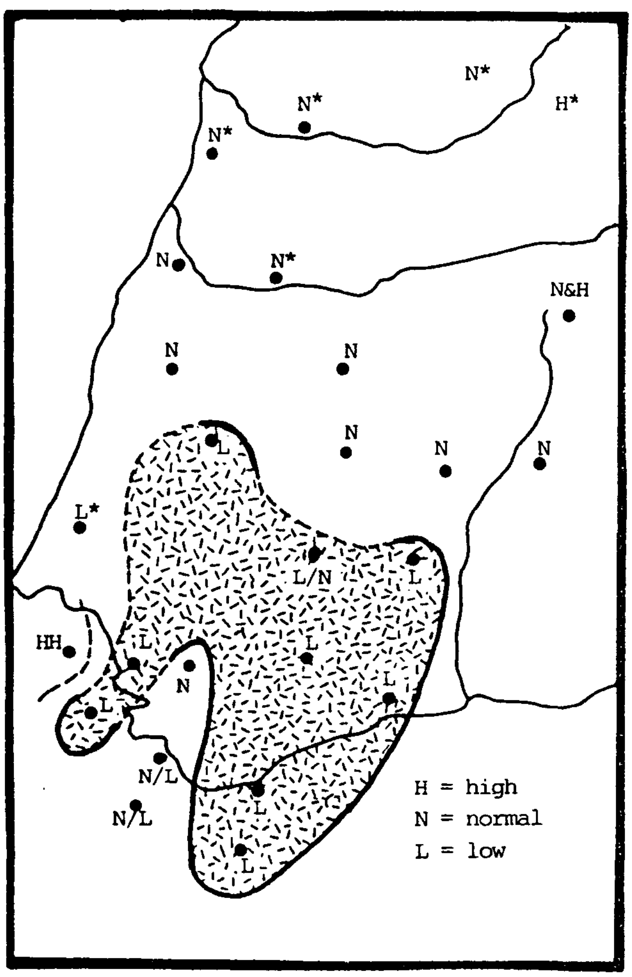


FIGURE 70. Distribution of relatively high, normal and low volatile matter values for upper Rewanui coals in the Rapahoe Sector (ie., high, normal and low in terms of values expected for the rank of each sample).
* indicates dmmsf of Suggate (1959) in cases where no ash constituents data available for individualised calculation of mineral matter free volatile matter.

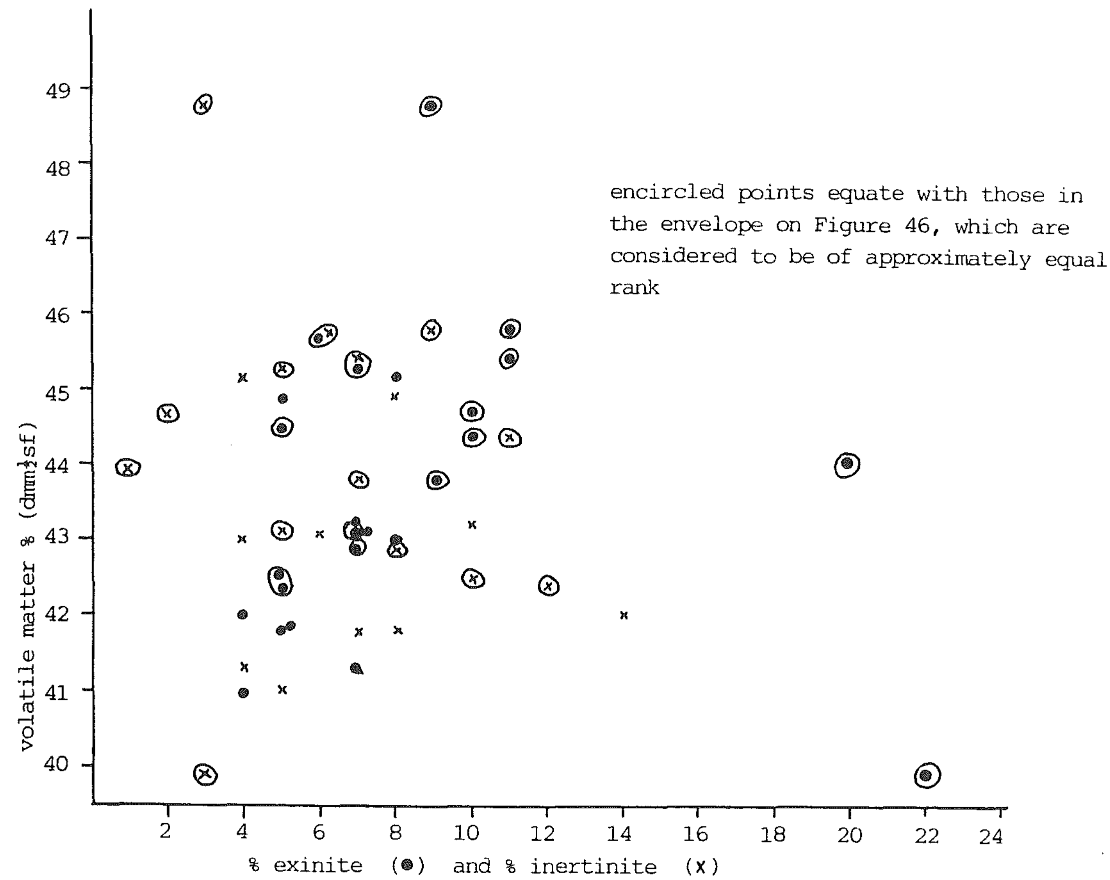


FIGURE 71. Relationship between volatile matter and coal macerals for upper Rewanui coals from the Rapahoe Sector.

matter for all the samples listed in Table 6 for which data are available. An envelope encloses sample points for the southwestern area where rank variation is considered to be slight (>9% moisture, Fig. 67a). Samples from Drillholes 633 and 648, which are spaced only 500m apart, occupy extreme positions within this envelope, whereas samples from 650 and 644, which are 1300m apart, lie adjacent on the plot. This distribution indicates that the marked variations in coal properties exhibited by samples in the southwest are a consequence of variations in coal type rather than rank. If the variability between samples were attributed to rank changes it would be necessary to invoke an absurdly complex pattern of rank variation.

The vitrinite reflectance/volatile matter relationship for coals of the Rapahoe Sector (Fig. 72) is weak compared with similar plots for coals from Pike River and Buller Coalfields (see 4.3, 4.5 & 4.6). Some of the scatter may be due to inter-laboratory bias.

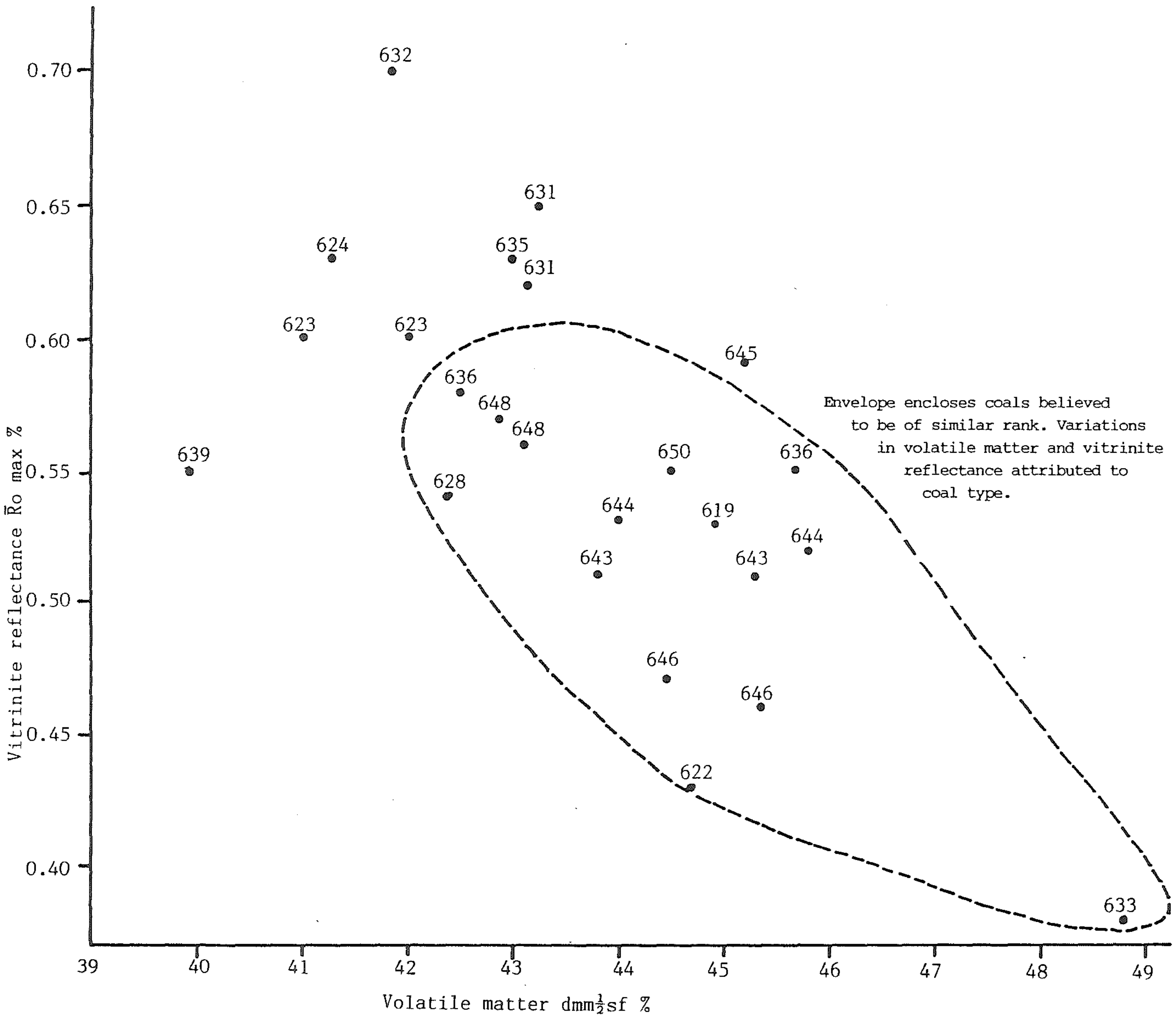


FIGURE 72. Relationship between vitrinite reflectance and volatile matter (dmm½sf; Appendix 8) for upper Rewanui coals in the Rapahoe Sector

Samples showing major deviation from the general relationships (e.g., coals from Drillholes 622 and 639) were analysed by ACIRL (see Sources, Table 6), whereas most of the remaining samples were analysed by CRA in New Zealand. Inquiries initiated by T. E. Bates (pers. comm.) regarding discrepancies between ACIRL and CRA volatile matter values (daf) recently led ACIRL to admit that their analytical procedure prior to 1984 resulted in values for Pike River Brunner coals which were up to 6% low. The problem may be less severe in the case of the lower swelling Rapahoe Sector coals, but could still be causing significant discrepancies. Furthermore, the Rapahoe Sector reflectance values were measured by ACIRL personnel, whereas those for Pike River and Buller coals were determined by me.

4.4.3 Specific coal types and their inferred paleoenvironmental significance

(a) Introduction. In terms of traditional maceral analysis, most Upper Rewanui coals in the Rapahoe Sector are of rather uniform type, with vitrinite approximately 80% and inertinite and exinite usually in the range 3 to 10%. However, investigation of correlatives at Pike River Coalfield (see 4.3) has shown that maceral textures, sub-varieties and associations are also important, and that two coals with similar maceral proportions, and hence superficially similar types, can be petrographically and chemically quite distinct and of substantially different genesis. Unfortunately the available ACIRL maceral analyses are of limited assistance for differentiation of important coal type categories in the Rapahoe Sector. In particular, no values are recorded for "suberinite" (resin impregnated cell walls) despite the importance of this maceral in some samples. Suberinite appears to have been attributed to another exinite variety, probably resinite. In addition, the vitrinite group is not subdivided into telocollinite, desmocollinite, and vitrodetrinite, which would assist differentiation of coal types in the Rapahoe Sector. In order to avoid repetition of the petrographic analyses, particularly in view of time constraints, the writer concentrated on qualitative observations of maceral characteristics in the current investigation.

It is important to stress that all Rapahoe Sector coals have some features in common, and that in the grain mounts studied, a substantial proportion of coal particles are frequently not of distinctive type. Therefore in order to define type variability it is often necessary to seek out textural and/or compositional features which are more or less characteristic of that coal and which distinguish it from others. The type categories discussed in this section have been defined qualitatively, but are considered to be valid. With more work, some of the important distinguishing features could be quantified, e.g., by some form of microlithotype analysis. The particular type category to which each Upper Rewanui coal most closely belongs is shown in Table 6. Due to a lack of information, some coals have not been assigned a type category. Classification as high or low in volatile matter yield, where given as a type parameter, is always used in the sense of relatively high or low compared with the expected value, given the inferred rank of the sample (see 4.4.2).

(b) Type I is a large group of coals characterised by a normal to relatively high volatile matter, and an assemblage of waxy and resinous macerals which appear to have been derived from a distinctive swamp flora. Figures 73 to 78 illustrate characteristic features of this group. Phyllovitrinite, which is telocollinite "sandwiched" between cutinite and exhibiting well preserved, often resinous tissue structure, is a common element. So are suberinite, as defined previously, and various forms of resinite, notably a variety known as fluorinite because it fluoresces a vivid blue or green at the lower-rank end of the bituminous coal range. All of these macerals are consistent with a conifer flora (Stach et al. 1982), and the association will be referred to as "conifer" in this report. The resinous component of the maceral assemblage may contribute in small degree to the relatively high volatile matter yield of Type I coals. However, the generally poor relationship between exinite content and volatile matter (Fig. 71) strongly suggests that variation in vitrinite chemistry is the principal influence on volatile matter yield.

The distinctive "conifer" maceral assemblage is often best developed when associated with clastic mineral matter, supplied during flooding of the peat swamp. Although this relationship could imply that "coniferous" elements in the coals are actually allochthonous, i.e., washed in by floods after derivation from surrounding areas, a frequent occurrence of "coniferous" material in very clean horizons which show no evidence of reworking suggests that it is likely to be autochthonous. However, in such cases it is usually

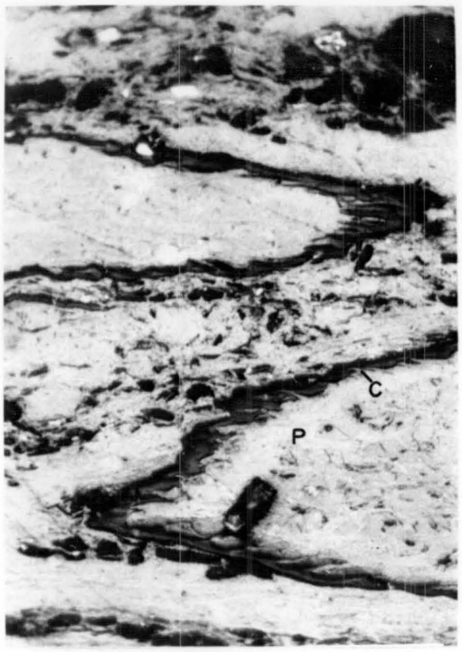


FIGURE 73.

Phyllovitrinite (P, 'leaf' vitrinite) with associated cutinite (C), in mineral matter rich sample. D seam, Strongman Mine, horizontal field 0.15mm.

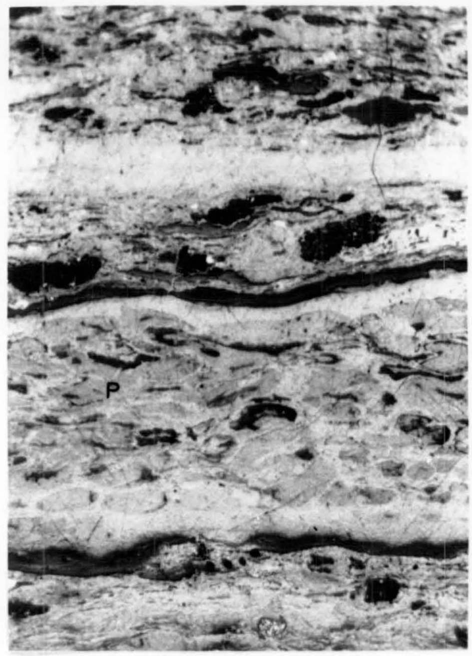


FIGURE 74.

Phyllovitrinite (P), with well defined tissue structure. Seam 2, drillhole 641 (29/220), horizontal field 0.15mm.

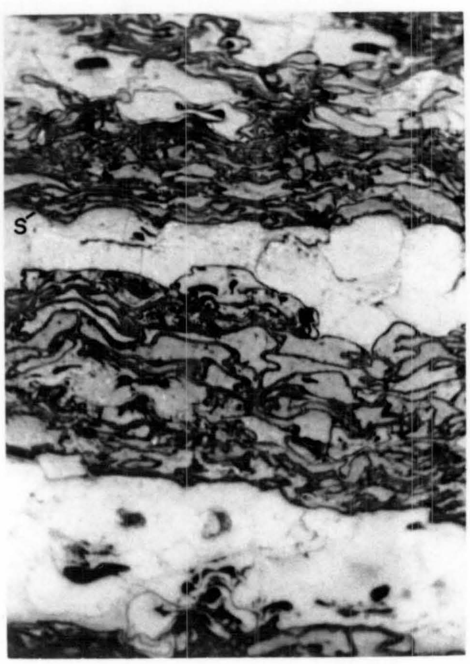


FIGURE 75.

Suberinite (S, resin impregnated cell walls). Seam 3, drillhole 641 (29/213), horizontal field 0.15mm.

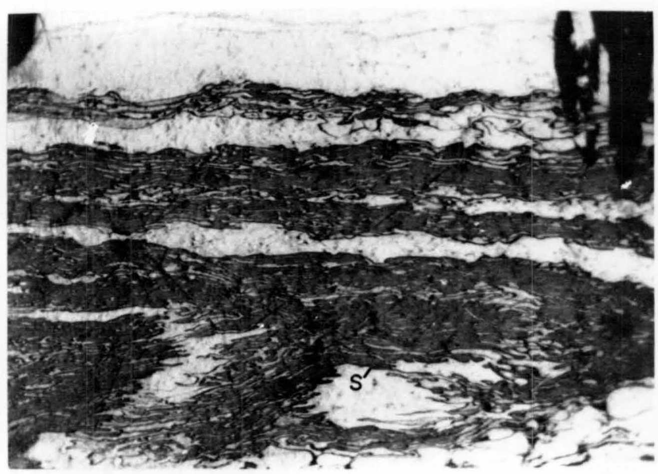


FIGURE 76.

Suberinite (S), of a character very common in Type I coals. Seam 2, drillhole 639 (29/156), horizontal field 0.25mm.

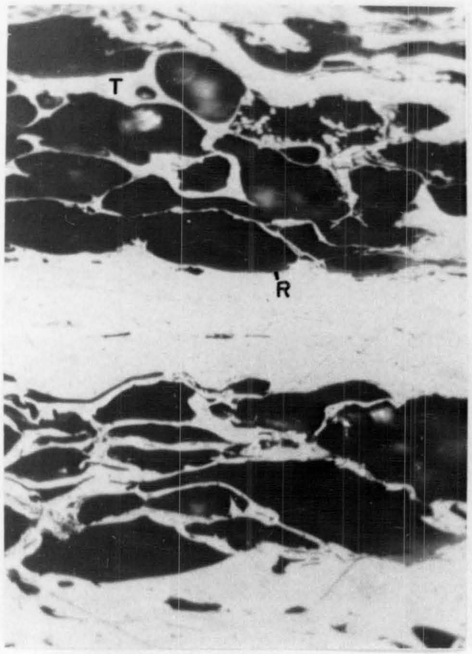


FIGURE 77.

Resinite (R) in telinite (T). D seam, Strongman Mine, horizontal field 0.15mm.

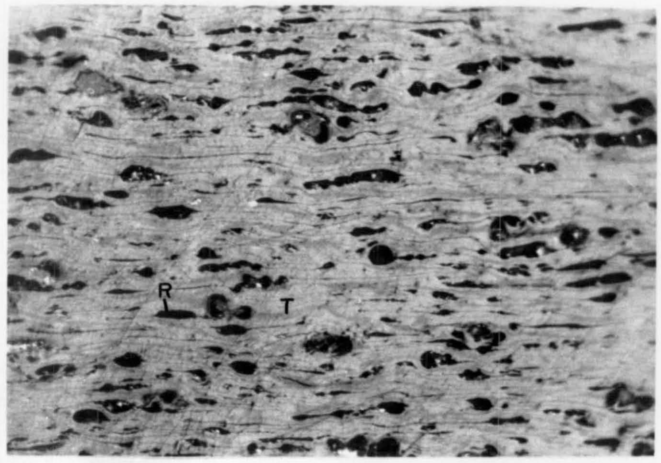


FIGURE 78.

Telocollinite (T) with some resinous cell contents (R). Seam 2, drillhole 641 (29/220), horizontal field 0.25mm.

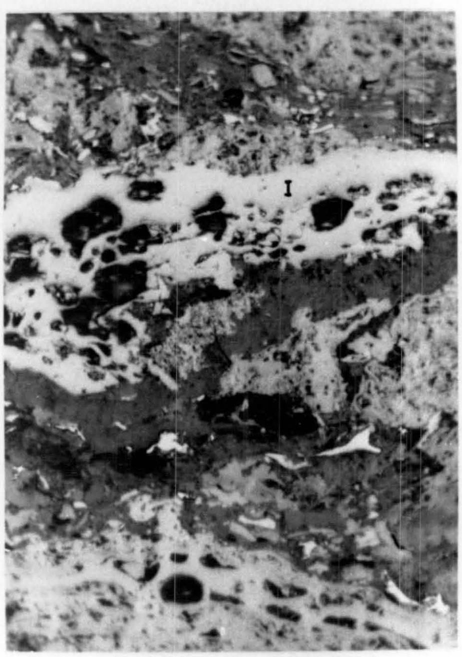


FIGURE 79.

Horizon dominated by inertinite(I), probably in-situ. Seam3, drillhole 636 (29/860), horizontal field 0.15mm.

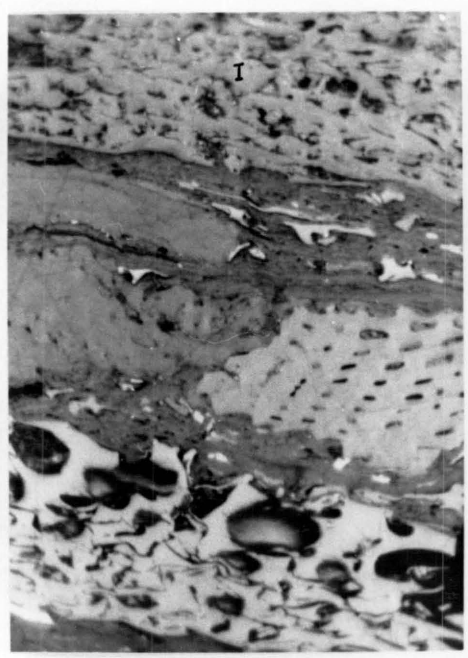


FIGURE 80.

Horizon dominated by inertinite (I), probably in-situ. Seam 4, drillhole 638 (29/664), horizontal field 0.25mm.

possible to infer proximity to streams (as opposed to derivation from them) on paleogeographic grounds. Overall, the most probable explanation appears to be that the "coniferous" flora grew in situ and most peat was autochthonous, but that this floral assemblage preferred a location near to streams carrying sediment, which suggests that the flora depended on an ample supply of nutrients.

Type I coals occur mainly in the north and northeast of the Rapahoe Sector. These coals are similar in character to the "northern M4" samples described from Pike River Coalfield, which are attributed to poorly drained swamps (see 4.3).

(c) Type II coals contrast with Type I examples by having relatively low volatile matter and sparse "conifer" elements. Most Type II coals have thin horizons in which fusinite and semifusinite predominate and appear to be autochthonous (Fig. 79 and 80), implying occasional dessication of the peat surface. More frequently, the inertinite is somewhat disordered and mixed with other macerals (Fig. 81) in a manner which suggests some reworking, but a general absence of mineral matter in this association is evidence that the inertinite was generated by dessication within the swamp, and only locally transported by internal swamp drainage. Reworked clasts of oxidised peat also occur (Fig. 82). Despite the existence of local concentrations, inertinite is overall a minor constituent of Rapahoe Sector seams, rarely exceeding 10%. Variations in inertinite content do not significantly influence volatile matter levels, for example the thick seams in Drillhole 648 (29/235 & 230) have 5 to 8% inertinite in contrast to 12% in the Drillhole 628 seam intersection (26/376), and there is no significant difference in volatile matter yield.

The low volatile matter of Type II coals compared with others in the Rapahoe Sector is attributed to the previously discussed influence of relatively well oxygenated peatification on vitrinite chemistry (see 4.2, 4.3), and the evidence of occasional peat dessication supports this interpretation. The swamps are therefore considered likely to have had relatively low water tables. The important thick seam intersections in the southwest of the Rapahoe Sector consist mainly of Type II coals. These coals are similar to the "southern M4" samples described from Pike River Coalfield, which are attributed to well drained swamps.

FIGURE 81.

Reworked inertinite (e.g., I). Absence of mineral matter suggests transport has occurred in streams arising within the swamp. Seam 1, drillhole 628 (26/376), horizontal field 0.25mm.

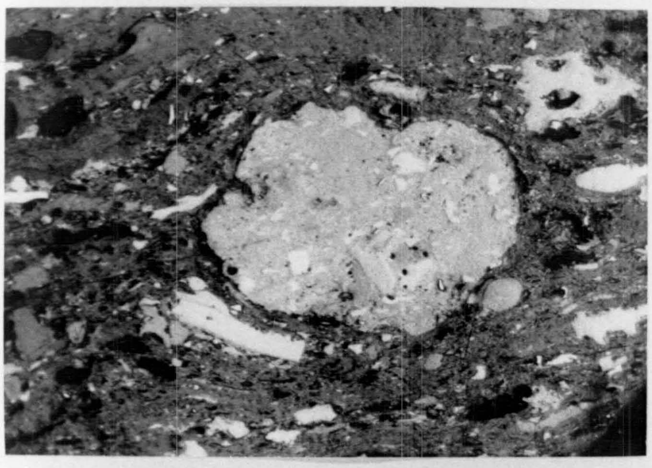


FIGURE 82.

Reworked clast of oxidised peat. Seam 4, drillhole 638 (29/664), horizontal field 0.25mm.

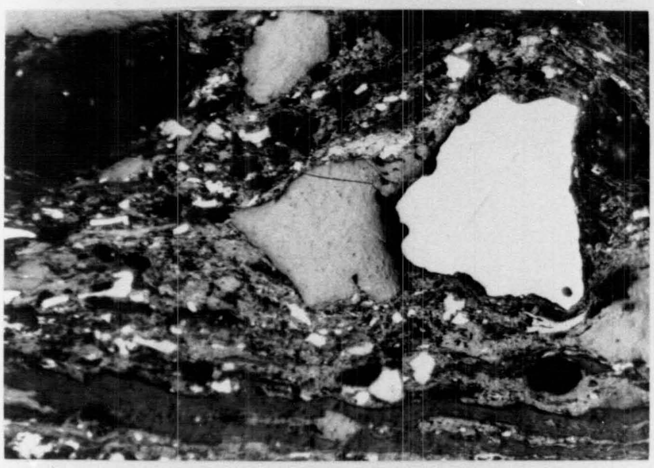


FIGURE 83.

Mixed assemblage of fragmented macerals, associated with mineral matter (quartz sand grain, black, top left). Seam 2, drillhole 646 (29/033), horizontal field 0.25mm.

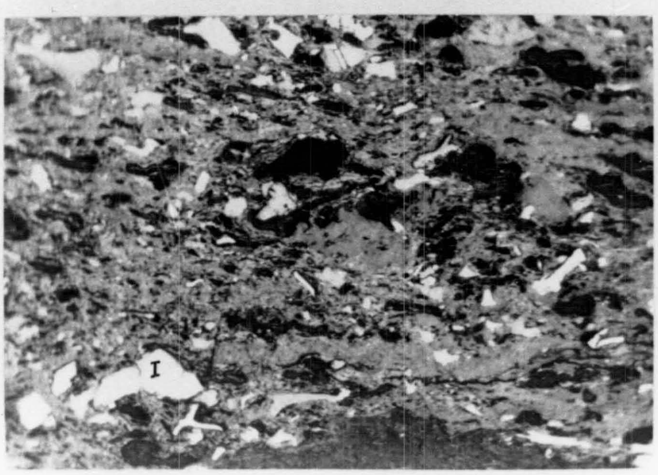


FIGURE 84.

Mixed association, with prominent inertodetrinite (I). Seam 1, drillhole 633 (26/662), horizontal field 0.25mm.

(d) Type III coals have a moderate to high volatile matter character, and reflectances tend to be significantly lower than for Type II coals of equivalent rank. The "conifer" element of Type I is usually sparse or absent in Type III, as in II. A characteristic feature of Type III coals is a transported assemblage of fragmented macerals (vitrodetrinite, liptodetrinite, and some inertodetrinite), with and without mineral matter (Figs 83 and 84). In these coals inertinite is almost always fragmented and occurs in a "mixed" association, which suggests that it was derived largely from outside the swamp, or from other parts of the swamp. The combination of high volatile matter, relatively low reflectance, and frequent transported assemblages is evidence of a consistently high water table, hence poor oxygenation. The generally low mineral matter content (Table 6) indicates that wet conditions were usually manifested as ponding and internal stream drainage rather than flooding by streams originating outside the swamp. This would be consistent with the usual paucity of "coniferous" constituents, if these required a good nutrient supply as previously hypothesised. Ponding may also be indicated by sporadic grains of sand and silt occurring without the clay which is typical of flood accumulations (Figs 85 and 86). These grains are considered likely to have entered the swamp attached to floating plant debris.

Type III coals are similar in many respects to some "M3" coals described from Pike River Coalfield (see 4.3), which are attributed to swamps featuring internal reworking of peat by streams.

(e) Type IV is a category for which I have so far examined only one example. This sample is characterised by abundant thin but distinct micro-laminae of very fine inertodetrinite and other fragmented macerals (Figs 87 and 88). Mineral matter is not an important constituent of these mixed layers. A likely origin is settling of fine plant debris in standing water, and as the example in question occurs near the transition from fluvial to lacustrine sediments in the uppermost Rewanui a lake margin setting is probable.

Seam 4 in Drillhole 623 (26/267) appears likely to be a Type IV coal because it has abundant inertinite (ACIRL determination), and is overlain by Goldlight mudstone. Other members of this group are likely to occur wherever coal is found at and above the transition from Rewanui fluvial sediments to Goldlight lacustrine mudstone

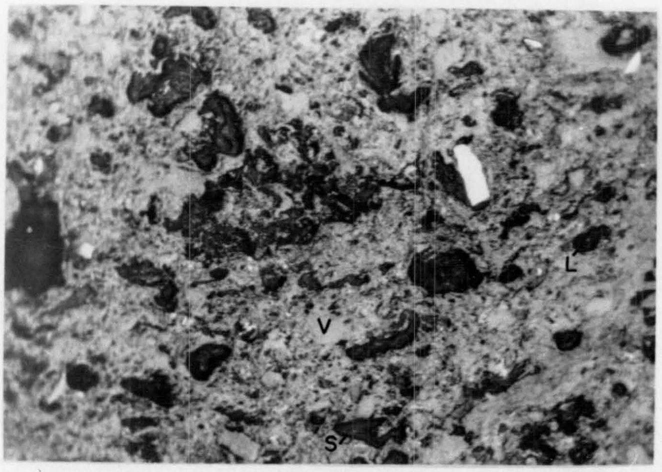


FIGURE 85.

Mixed association, mainly sporinite (S) and liptodetrinite (L), with vitrodetrinite (V). Seam 1, drillhole 633 (26/662), horizontal field 0.25mm.

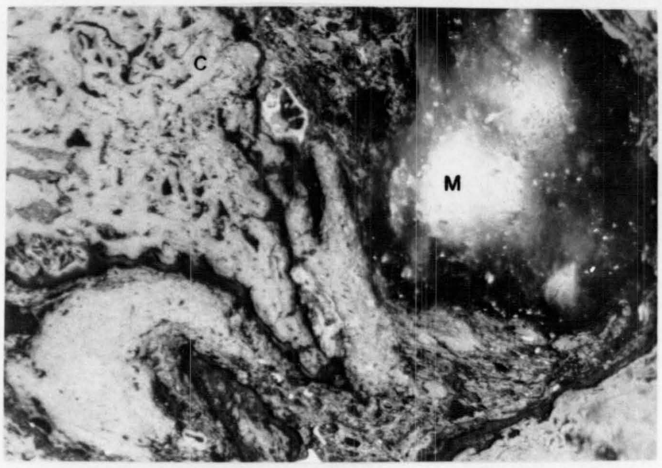


FIGURE 86.

'Coniferous' flora (C) with mineral matter (M). Seam 1, drillhole 644 (29/075), horizontal field 0.25mm.

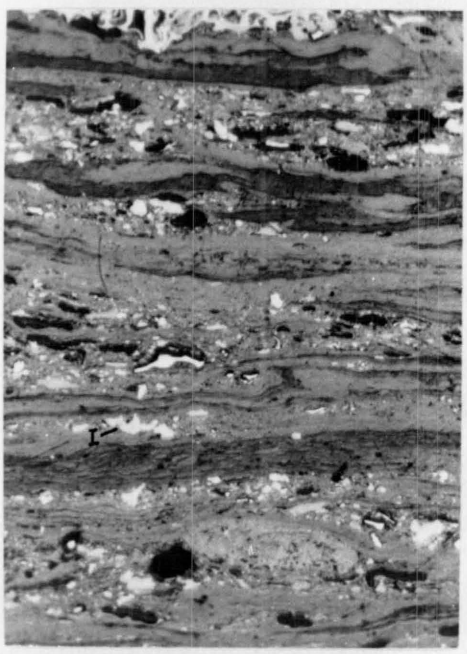


FIGURE 87.

Microlaminae of inertodetrinite (I), possibly of lacustrine origin. Seam 8, drillhole 640, horizontal field 0.15mm.

FIGURE 88.

Microlaminae of inertodetrinite (I), possibly of lacustrine origin. Seam 8, drillhole 640 (29/140), horizontal field 0.15mm.

(e.g., thin seams interbedded with mudstone in basal Goldlight sediments on the Rewanui incline, near Dunollie; the thin seam in Drillhole 653 [29/738], for which full analytical data are not available).

4.4.4 Models of peat accumulation in the Rapahoe Sector

(a) Introduction. Given the present understanding of Paparoa coal types, and thus of local swamp conditions, it would be possible to propose regional paleoenvironmental models with some confidence if drillholes could be correlated reliably. Unfortunately, stratigraphic variability renders the existing drillhole spacing too broad for reliable correlation. In addition, the mineral matter content of seams is influenced by multiple source areas and complex drainage patterns to the extent that geophysical profiles change radically over short distances and are rarely useful for correlation. The sensitivity of type characteristics to local depositional circumstances limits the usefulness of type studies for correlation purposes, because substantial variations are likely to occur from place to place within a single seam. For these reasons, there is some uncertainty concerning the models presented and justified in this section. Expansion of coal petrological and sedimentological studies would refine these working hypotheses; however, conclusive testing awaits further drilling and if feasible, seismic exploration.

(b) Peat accumulation in the south. Several drillholes in the south of the Rapahoe Sector have intersected exceptionally thick coal seams e.g., 628: 10.65 m, 633: 10.3 m, 636: 12.1 m, 638: 18.0 m, 646: 11.2 m (corrected for dip). These seam intersections are particularly striking in view of the general thinness of coal measures in this area - for example, the Rewanui in Drillholes 633 and 646 is almost 50% coal. Previous discussion has identified the southwest of Greymouth Coalfield as a zone of relatively slow subsidence (Fig. 19), which was less affected by major fluvial activity than adjacent areas to the north and east (see 3.2.2(g)). It has been suggested that these factors favoured uninterrupted peat accumulation. Correlation of thick southwestern seams is currently a major industrial issue affecting assessment of the Rapahoe Sector. Unfortunately the contact between Rewanui fluvial lithologies and the overlying Goldlight lacustrine mudstone is potentially diachronous within the Sector. Therefore correlation of drillholes must be achieved on other grounds.

As described in Section 4.4.3, several thick seams in the southwest are of a distinctive low volatile character (Type II), consistent with accumulation in relatively well drained swamps. If the Rewanui-Goldlight contact is regarded as diachronous, the *simplest* model in terms of seam correlation attributes all thick Type II coals to a single horizon (Fig. 89). This hypothesis implies extensive peat accumulation, limited to the north and east by fluvial activity and to the south by the basin margin. Although discontinuities in this horizon are not apparent in Figure 89 except at Drillhole 650, the potential for local splitting and barren zones is acknowledged. The relatively low volatile matter yield of these coals indicates that the swamps were comparatively well drained. Sporadic inertinite layers reflect occasional dessication, an unusual characteristic in Rewanui coals. Given the lithostratigraphic evidence for relatively slow subsidence and remoteness from major centres of fluvial activity, the distinctive type of these southwestern coals is suggestive of peat accumulation in bogs which were somewhat raised i.e., ombrogenous. Raised bogs form in stable areas where rainfall is normally sufficient to saturate the peat and inhibit decomposition. Drainage channels tend to arise inside the swamp, radiating towards the periphery and the convexity of the swamp margin is sometimes sufficient to inhibit flooding of the swamp by external streams. Consequently these swamps can become deficient in nutrients compared with those occupying depressions which regularly receive floodwaters from outside. A nutrient deficiency would be consistent with the hypothesis in Section 4.4.3 that the distinctive "conifer" flora, lacking in most Type II coals, required a good nutrient supply.

The stratigraphic relationships of Type III coals near the base of the Rewanui Member in Drillholes 644, 646 and 633 indicate that these seams could correlate with those in Drillholes 628, 636, 638 and 640. The petrography of the Type III coals indicates accumulation under relatively wet swamp conditions, which is consistent with their higher volatile matter yield compared with the Type I examples, and also accounts for the relatively low reflectance of seams in Drillholes 646 and 633. Paleogeographic implications of this model are illustrated in Figure 90.

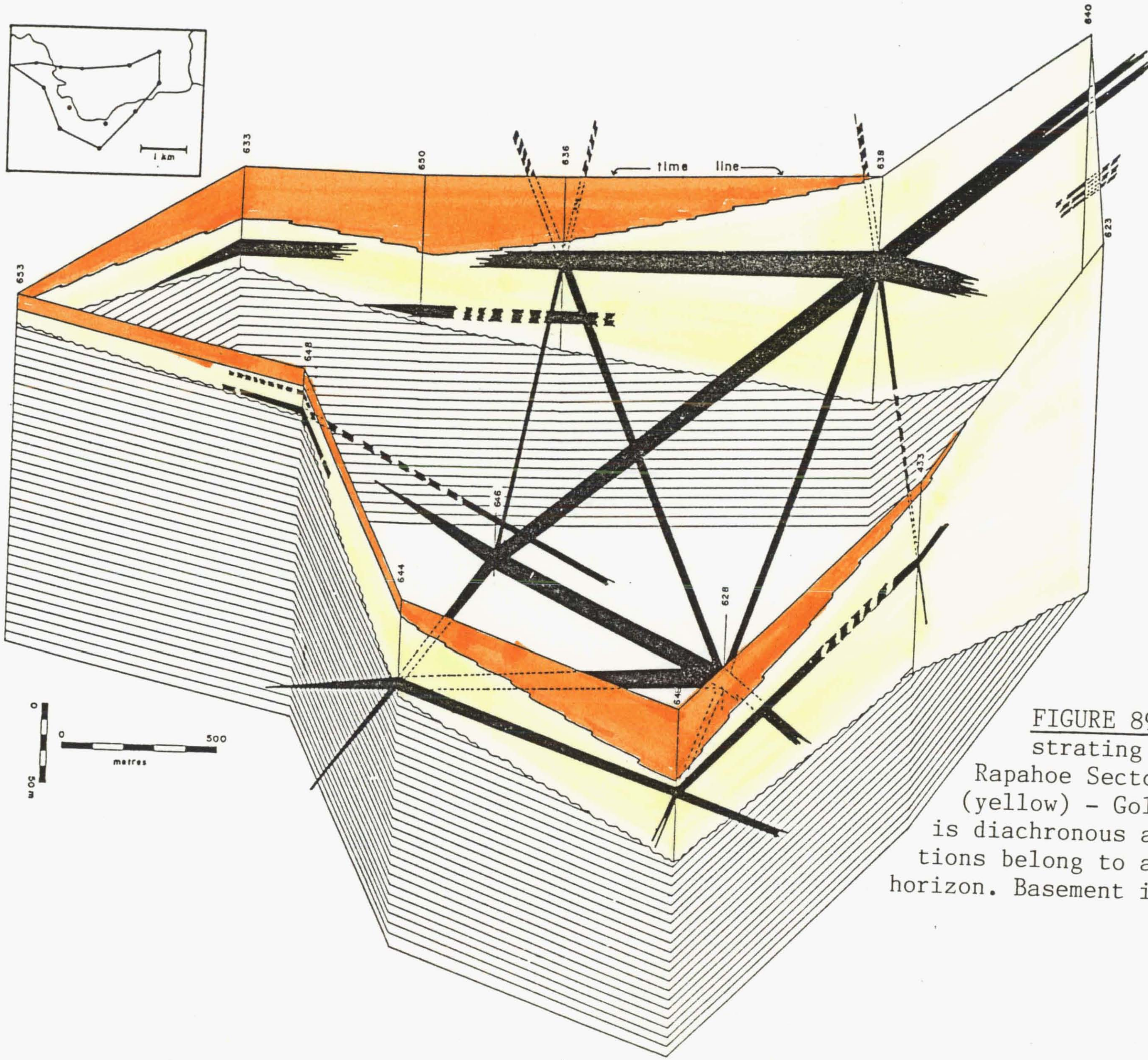


FIGURE 89. Fence diagram illustrating a model for the southern Rapahoe Sector in which the Rewanui (yellow) - Goldlight (orange) contact is diachronous and major seam intersections belong to a single coal-bearing horizon. Basement is hatched.

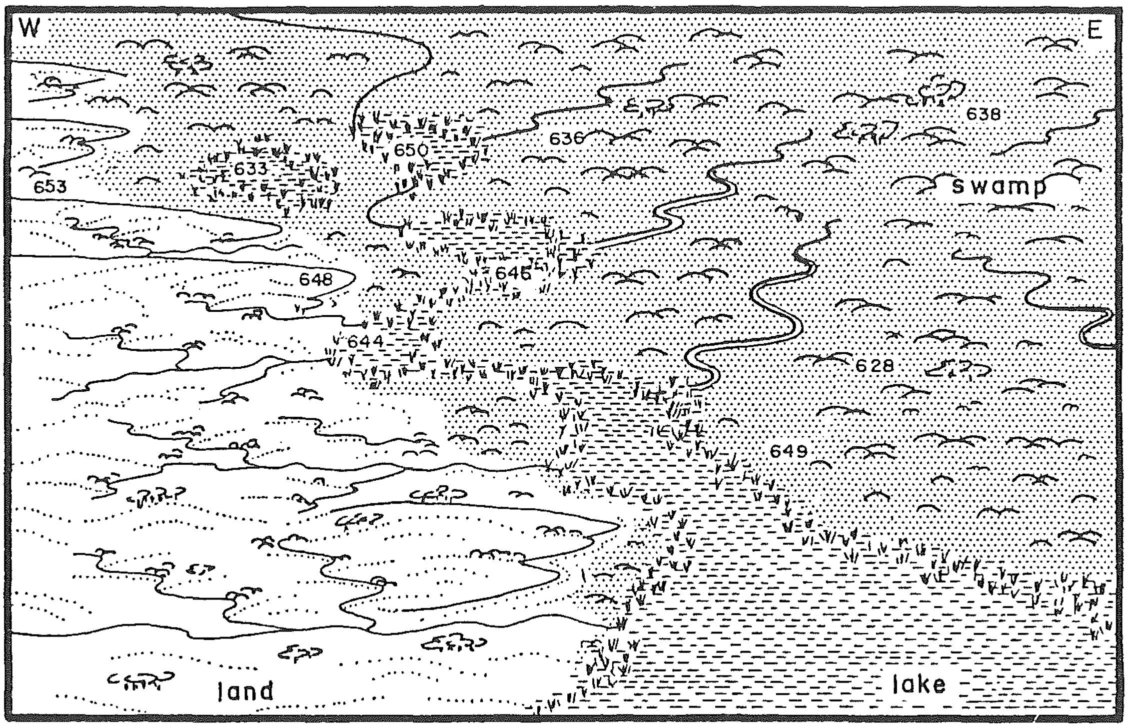


FIGURE 90. Hypothetical paleogeographic reconstruction consistent with the correlation model proposed in Figure 89 for peat accumulation in the southern Rapahoe Sector.

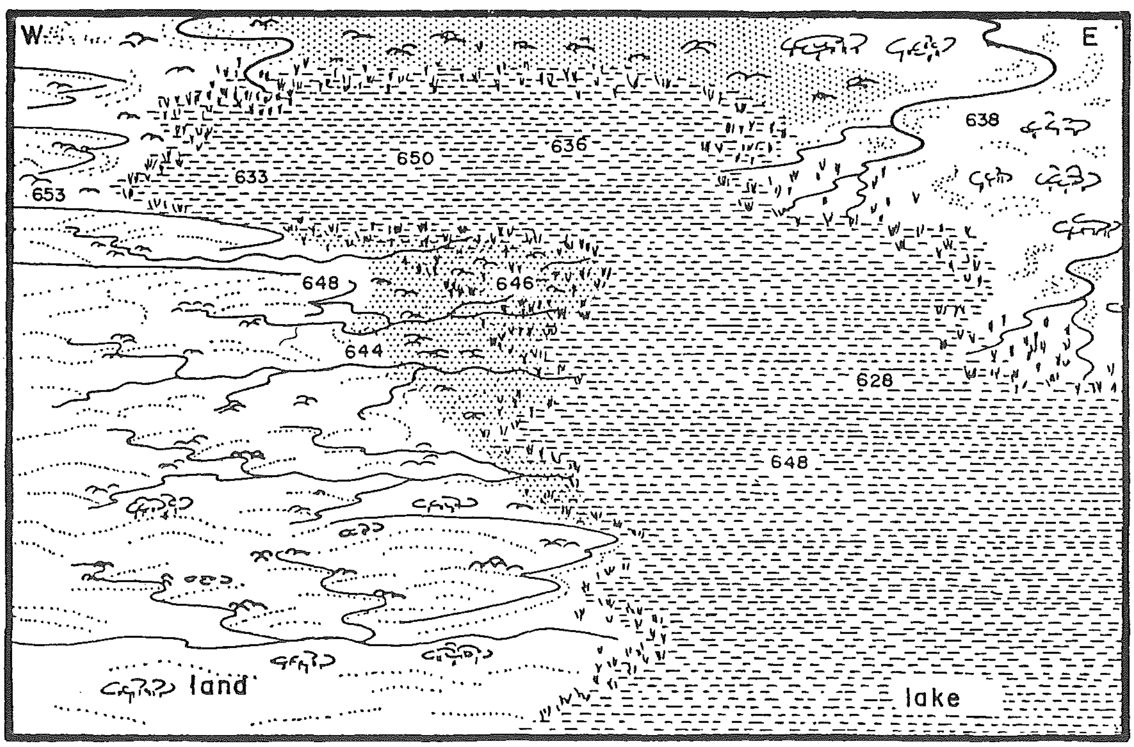


FIGURE 91. Hypothetical paleogeographic reconstruction for the same area as in Figure 90, showing drowning of the peat swamps by an arm of the Goldlight lake.

Although the above model is attractive for its simple seam correlation, it is open to potential criticisms which must be considered. Firstly, mining in the northern Rapahoe Sector has shown that a large seam thickness is no guarantee of seam continuity, hence correlation over distances greater than a few hundred metres is hazardous. Thorburn's (1981) isopachs of Strongman Mine seams illustrate the potential complexity of seam geometry. The implications for other parts of the Rapahoe Sector are obvious, and cannot be completely disregarded. However, the greater tectonic stability and lesser fluvial activity in the southwest compared with the Strongman area can be expected to have produced relatively persistent seams with simpler geometry.

A second potential objection to the proposed model concerns its implications regarding the Rewanui-Goldlight contact. Bowman (1982) believes this contact to be a useful time plane in the southwest, if not in the rest of the Rapahoe Sector. He supports this hypothesis largely by observations that the transition from fluvial to lacustrine sediments in any one drillhole is abrupt and complete, with apparently no oscillation of lake level. This argument is not conclusive because a gradual rise in base level need not be characterised by oscillations of the magnitude required to unduly complicate the lacustrine-fluvial sediment interface. In addition, some of the finer "fluvial" lithologies are likely to be proximal lacustrine sediments, in which case the precise onset of lacustrine conditions, and also the occurrence of oscillations in lake level, would be difficult to detect with certainty.

The reconstruction in Figure 90 is hypothetical, but consistent with paleogeographic information. In view of the basin configuration, with high ground to the southwest and persistent fluvial activity in the northeast and northwest, the Goldlight lacustrine transgression is likely to have followed a complex front (Fig. 91). The extreme thinness of Rewanui (i.e., fluvial) sediments in Drillholes 653 and 648, coupled with known paleoslope trends in the region, indicate that lacustrine transgression occurred relatively late in these upslope positions. Figures 92b and 93b depict cross sections traversing the southwest quadrant of the Rapahoe Sector, using the correlations proposed above. The "time line" of Figure 89 constitutes the reference datum for these sections. For comparison, sections constructed with the Goldlight-Rewanui contact as a time-line are also shown (Figs

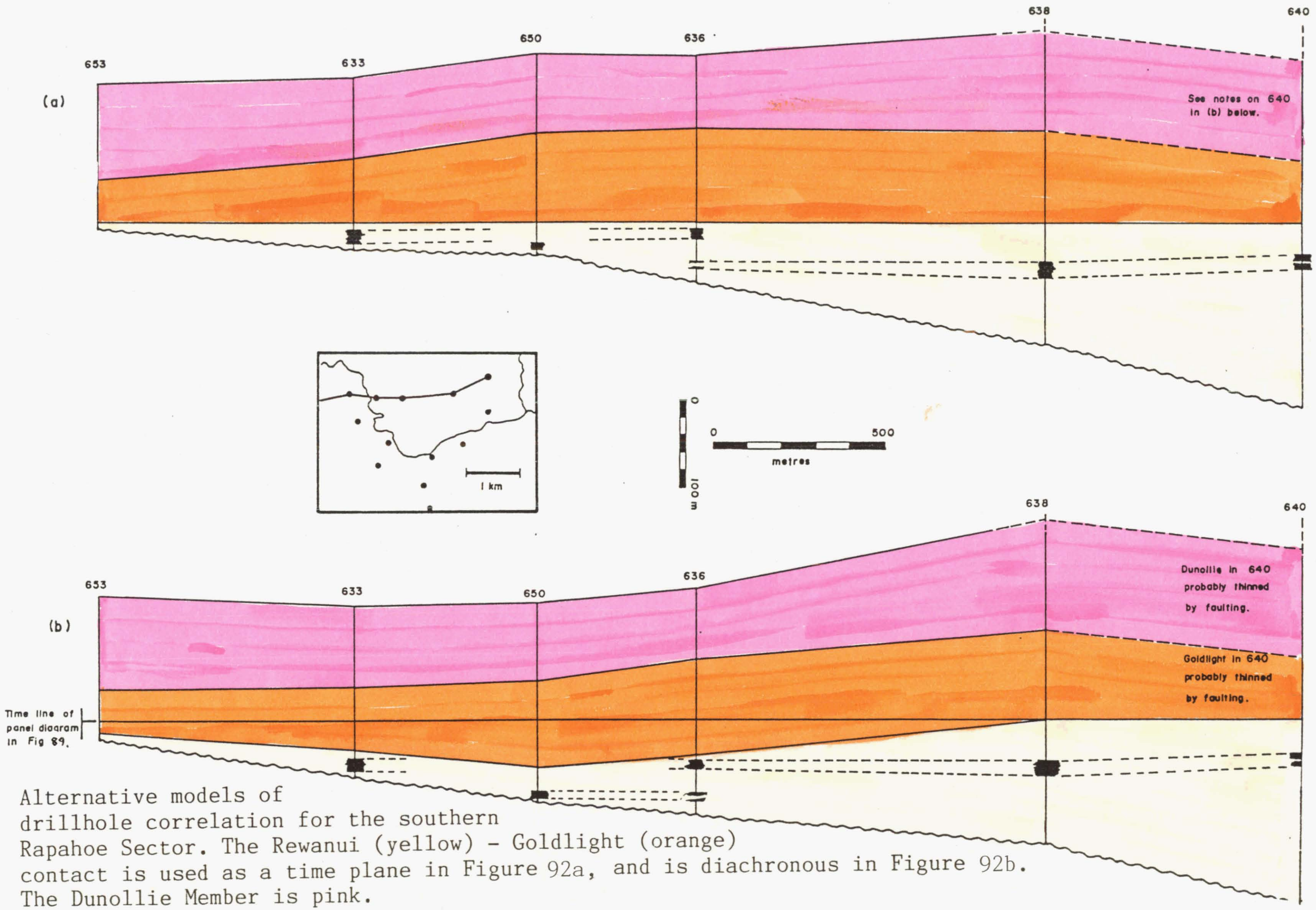


FIGURE 92. Alternative models of drillhole correlation for the southern Rapahoe Sector. The Rewanui (yellow) - Goldlight (orange) contact is used as a time plane in Figure 92a, and is diachronous in Figure 92b. The Dunollie Member is pink.

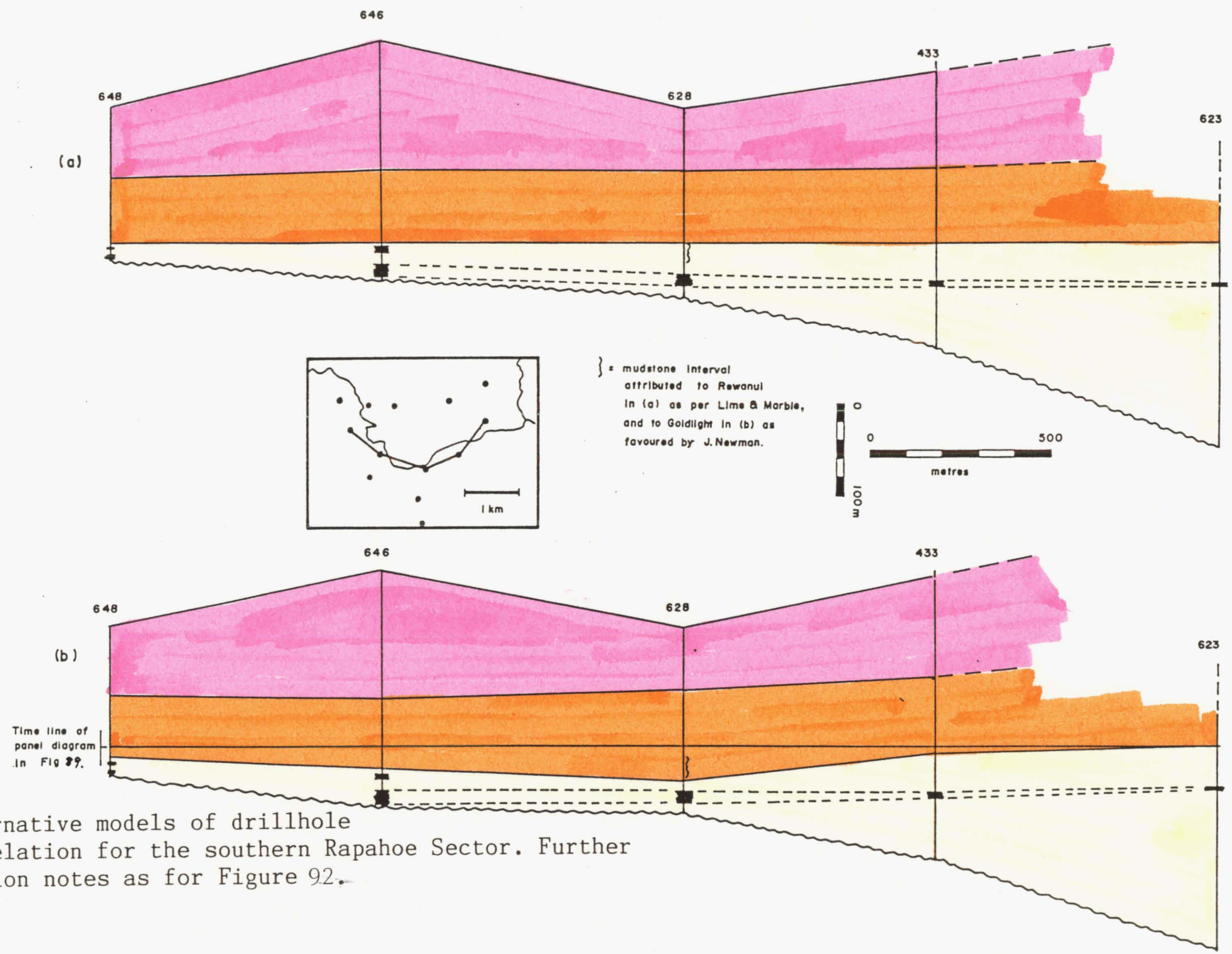


FIGURE 93. Alternative models of drillhole correlation for the southern Rapahoe Sector. Further caption notes as for Figure 92.

92a and 93a). Neither interpretation causes unacceptable complexities in configuration of the basin floor, although if the exact path of the section line is considered a case can be made that Figure 92b is more consistent with expected basement configuration than Figure 92a. The "b" versions, which infer a diachronous Goldlight-Rewanui contact, are of course complex in this regard, but overall this model is more realistic and it also results in the simplest interpretation of *seam* configuration.

Unfortunately, where drillholes are 1 km apart, as with 636 and 638, any particular seam correlation must be tenuous. Figures 94 and 95 are particularly interesting because they involve more closely spaced drillholes. Figure 94b, for example, results in a much better correlation between seams in Drillholes 644, 646 and 636 than Figure 94a, and Figure 95b shows good correlation between 644, 649 and 628, compared with no correlation in Figure 95a. Drillholes 628 and 649 are of particular importance, because they exhibit the most convincing evidence that lacustrine sedimentation commenced earlier in some places than others. Drillhole 628 is notable for having an intercalation of Goldlight-type mudstone between the main Rewanui sequence and a carbonaceous horizon within lacustrine mudstone. Assuming the interruption in lacustrine sediments is not due to fault repetition of carbonaceous uppermost Rewanui, this sequence implies early onset of lacustrine sedimentation at Drillhole 628, with a brief reversion to peat swamp conditions prior to a more sustained lacustrine event. Drillhole 649 supports this interpretation, if the seam at the top of the Rewanui correlates with the thick seam in Drillhole 628, as appears reasonable in view of the relatively small distance (500 m) between the sites. This reconstruction also results in the most likely basement configuration for this section. It may be significant that the nearby Drillhole 40 (drilled 1906), as logged (Gage 1952), showed a similar subdivision into 2 lacustrine events, separated by a sandy interval.

One implication of the "diachronous" model is that uppermost Rewanui sediments in Drillholes 644, 646 and 648 must be derived from the southwest, because a lacustrine arm separates these sites from the usual northwestern source (Figure 91). This proposal of a new source area raises the possibility of a difference in sediment composition. A suite of core samples was taken to test for this difference (Appendix 5), but a reconnaissance investigation of the

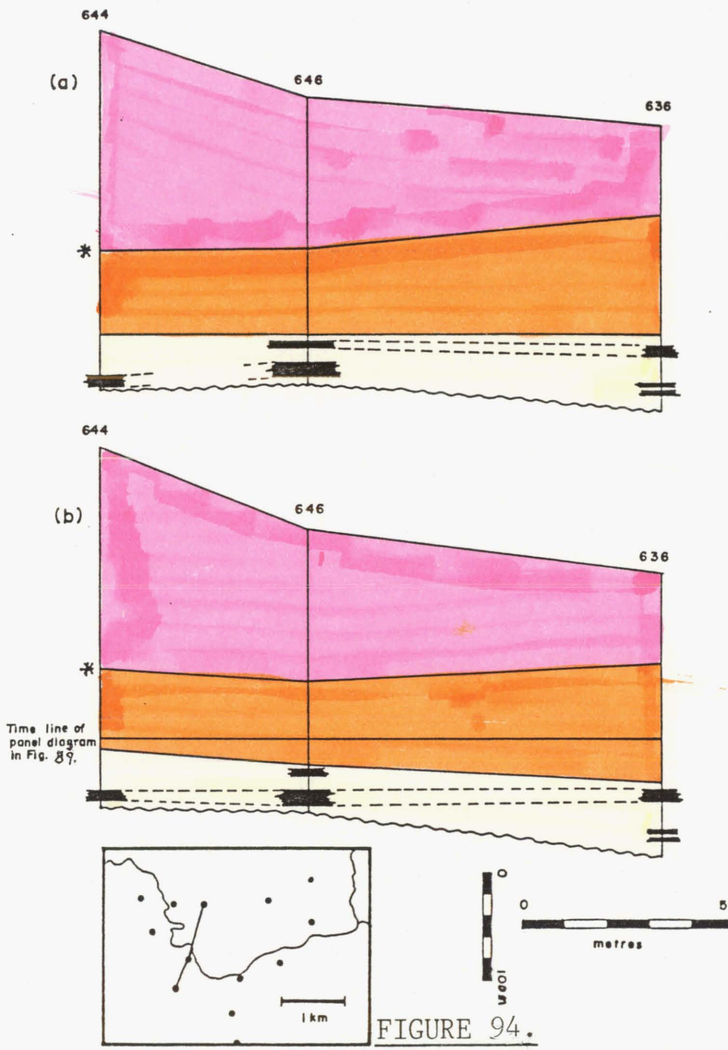


FIGURE 94.

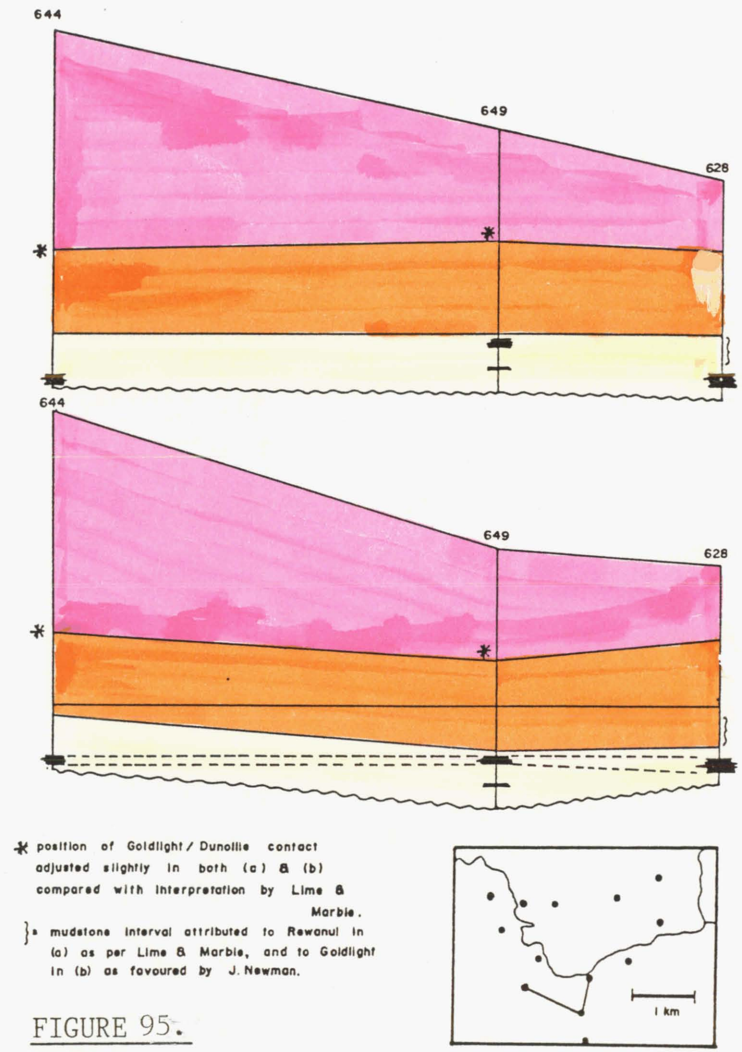


FIGURE 95.

Caption notes as for Figure 92.

samples indicates that upper Rewanui sediments tend to be of uniform composition throughout the southwestern zone.

(c) Peat accumulation in the north. Upper Rewanui coals have been worked at Strongman State Mine and the 10 Mile Creek mines, and known reserves remain in the vicinity of Strongman and to the south. Drilling undertaken near existing mines has established that it is difficult to extrapolate from mined seams to drillholes as little as 400m distant, even though some seams (e.g., C seam at Strongman Mine) are 1500m in extent. These correlation problems result from a tendency for seams to undergo very rapid changes in thickness, as demonstrated by Thorburn's (1981) Strongman isopachs. Thorburn attributes well defined northwest-southeast trends exhibited by coal and barren zones to streams draining through the swamp and causing sedimentation contemporaneous with peat accumulation. Thin mudstone horizons within the seams indicate that the swamps were flooded occasionally, and the general Type I characteristics of coals in the northern Rapahoe Sector indicate that swamps were essentially "topogeneous", i.e., low wetlands into which water tended to drain. This contrasts with the "ombrogenous" setting inferred for several of the thick southwestern seam intersections, and resulting differences in coal type have been discussed in Section 4.4.3.

Although local depositional circumstances can be inferred for the northern Rapahoe Sector coals, broader paleogeographic controls on swamp configuration, extent and character are as yet uncertain. Upper Rewanui coals in this area have traditionally been regarded as lake margin deposits associated with transgression of the "Goldlight" lake. A rise in base level and aggradation to lower the depositional grade undoubtedly did influence the onset of extensive peat accumulation towards the end of Rewanui sedimentation. However, a simple lake-margin model does not readily explain the seam characteristics and stratigraphy of coals in the area, particularly the occurrence of *multiple* seams separated by up to 30m of fine fluvial sediment. If a lake margin model is applied, the major paleogeographic features are a northwestern source area feeding a subdued alluvial fan apron, adjacent to a large lake. The peat swamps in this model occupy a transitional zone between the apron and the lake. This simple model does not explain why a prolonged period of peat accumulation (e.g., C seam, Strongman Mine) was separated from a similar later episode (e.g., D seam, Strongman Mine) by a long-lived influx of fine fluvial sediment. Alternation between very low sediment supply limited to small streams within extensive peat swamps, and relatively high sediment supply ending peat accumulation, is difficult to explain without inferring either changes in tectonic regime (e.g., uplift rates in source area), changes in climate, or substantial changes in the path of a *major* fluvial system. None of these alternatives is satisfactory. Invoking tectonics to explain *small-scale* stratigraphic features is rarely justified because such features can usually be explained by autocyclic mechanisms, i.e., effects resulting from adjustments in a fluvial regime, without recourse to fundamental tectonic events. Changes in climate, and consequent variation in runoff and sedimentation due to varying precipitation, should be invoked only if more likely mechanisms are lacking. There are no changes in coal type indicative of climatic change. Migration in and out of the area by a major *northwest-derived* fluvial system is not compatible with Upper Rewanui lithofacies trends in this part of the basin, which indicate that a subdued fault scarp nearby in the northwest supplied sediment via many *small* streams.

Consideration of stratigraphic and lithologic data, and information on coal seam characteristics, suggests an alternative to the lake margin paleoenvironmental model which provides a more complete explanation of Upper Rewanui peat accumulation in the Strongman Mine area. In this new model the lake margin is replaced by a meandering river flowing down the axis of the basin, to the east of the Rapahoe Sector. The existence of a major axial fluvial system carrying granitic sediments southwards during Rewanui sedimentation has already been discussed (see 3.2.2(g)) and the potential influence of this system on peat accumulation in the Rapahoe Sector can now be considered. It has been postulated earlier that the axial system was probably of braided character during middle Rewanui sedimentation. However, the upper Rewanui rise in base level and consequent decline in depositional gradient are likely to have resulted in a change to a meandering regime. A well exposed Rewanui sequence in the headwaters of Seven Mile Creek (Fig. 26) supports this hypothesis (see 3.2.2(g)) because it exhibits a change upwards from lenticular channelised sandstones, indicative of complex braiding, to more regular and extensive tabular sandstones consistent with meandering river sedimentation. Holes drilled a few hundred metres east of Strongman Mine (e.g., Drillholes 656 and 657) show that upper Rewanui sediments associated with coal seams have a granitic (quartzofeldspathic) composition, whereas middle Rewanui sediments are greywacke derived. This compositional change indicates that the axial fluvial regime expanded westwards during later Rewanui time, influencing areas previously occupied by the northwestern alluvial apron. The coincidence of this change in fluvial regime with the onset of thick peat accumulation in the northwest suggests a causal relationship, which is the basis of the model illustrated in Figure 96. In this model a meandering regime with associated levees caused ponding of drainage from the northwest, where sedimentation rates had declined due to lowered source area relief (see 3.2.2 (g)) and consequent swamp development. Peat accumulation was limited to the west by persistent sedimentation in the northwestern alluvial fan-toe region, and to the east by overbank sedimentation (levee, crevasse splay) adjacent to the meandering river. Within the swamp, peat accumulation was interrupted in places by sedimentation in small streams fed by the alluvial fan. In this model peat accumulation ceased when westward migration of the meandering river resulted in burial of the peat by overbank mudstones and siltstones. This is consistent with the very fine character of sediments in the interseam intervals at Strongman Mine. Quartzofeldspathic sandstones in the sequence further east at Drillholes 656 and 657 represent encroachment by the meandering channel itself, or by crevasse splays adjacent to the levee.

In an attempt to detect the influence of the axial fluvial system on sedimentation in the Strongman Mine area the successions above C and D seams were sampled both within the mine and in core from the Strongman West drilling programme (Appendix 5). Unfortunately, mudstones predominate in the area of the mine, although lithologies coarse enough for petrological investigation of composition occur locally. Strongman West lithologies are coarser but remote from the axial system and thus less likely to show an eastern influence. Reconnaissance examination of sandstone samples showed them to be of western derivation, dominated by greywacke clasts but with a small proportion of fresh angular feldspar, which is considered to derive from the northwestern granites (see 3.2.2(d)). This preliminary result suggests that sedimentation from the axial system was limited to overbank mudstones in the western (sampled) part of Strongman Mine, while the coarser sediments have a northwest origin as fan-toe sediments. Failure to detect quartzofeldspathic sandstones in the upper Rewanui at Strongman Mine prevents any reliable correlation between Strongman seams and coal further east in Drillhole 657 at

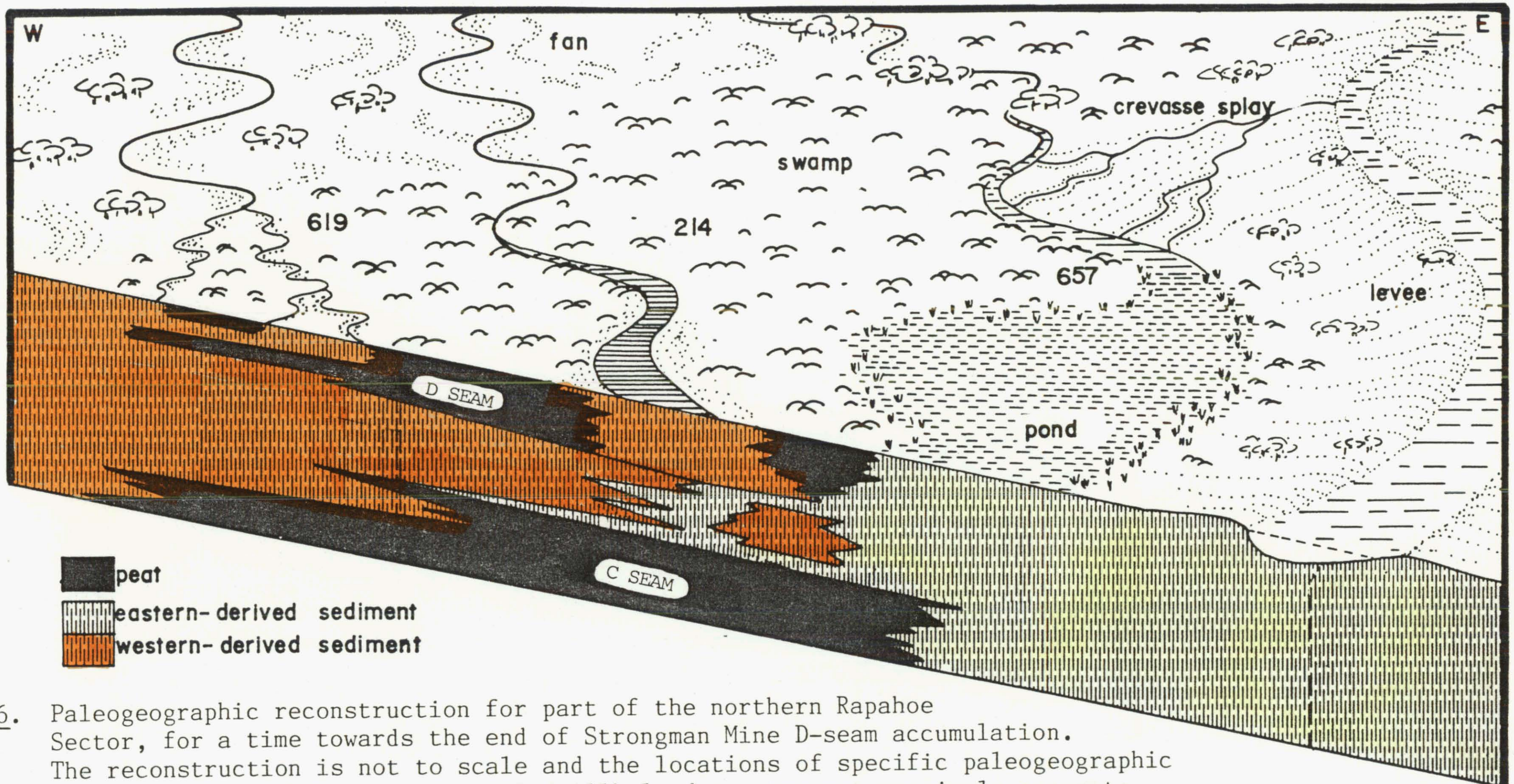


FIGURE 96. Paleogeographic reconstruction for part of the northern Rapahoe Sector, for a time towards the end of Strongman Mine D-seam accumulation. The reconstruction is not to scale and the locations of specific paleogeographic features, although based on actual drillhole data, are not precisely accurate.

present. If granitic sediments could be shown to occur above C seam, correlation with the lower seam in Drillhole 657 would be likely, with important implications for coal reserves east of Strongman. Only a few samples have been examined so far, hence closer investigation might produce more useful results. If current interest in the area warrants further work, an underground drillhole down from D seam in the East Heading of Strongman Mine should permit lithological correlation with the sequence in Drillhole 657, and identification of the seams.

The main difference between the above model of peat accumulation in the Upper Rewanui and earlier models is replacement of the proximal lake margin by a fluvial overbank setting. One important implication of this change is that the southern margin of successively younger coal seams in the northern Rapahoe Sector need not necessarily recede northward as implied by the lake-margin transgression hypothesis (Thorburn 1981). For example, it is possible that the 2 seams in Drillholes 631 are C and D seam, the latter having re-developed south of the barren zone running between Drillholes 614 and 629 (Fig. 12). Although previous workers have not favoured this correlation, there appears to be no conclusive evidence against it, particularly as correlation between Strongman Mine and Drillhole 631 is obscured by faulting.

Figure 96 attempts an approximate reconstruction of the area encompassing Drillhole 619, Strongman Mine and Drillhole 657, near the end of D seam accumulation. A reconstruction for C seam would be broadly similar, but the location and configuration of the swamps would vary. Reduction in quantity and also quality of coal to the west can be expected as a result of persistent fluvial activity in that area. Nevertheless, 2 promising upper Rewanui seams intersected in Drillhole 619 indicate that the limit of workable coal may be more than 1 km west of the Strongman Mine workings. Unless problems of structure or access preclude mining in this region, further exploration appears justified.

The eastern limit of workable coal has not been closely determined. The 2 4m seams (after correction for dip) intersected in Drillhole 657 indicate that good coal persists beyond the present Strongman workings, but 1 km further east data from Drillhole 99 (an early hole of uncertain date, which probably collared near the top of the Rewanui), shows only thin and dirty coal in a succession similar to that in Drillhole 632. Deterioration of coal in these holes is attributed to the activity of the axial fluvial system, flowing in a south-southwest direction. Consequently a strip of workable coal, with a width of perhaps $\frac{1}{2}$ km or so, may parallel the eastern margin of Strongman Mine from Drillhole 631 to north of Drillhole 657. If the eastern limit of workable coal is controlled by the axial system, as proposed, seam configuration could be very complex. As illustrated diagrammatically in Figure 96, at least 3 sedimentologic elements can be expected to interrupt peat accumulation: levees, small fans or "crevasse splays" caused by breaching of levees, and ponds developed on the floodplain. Figure 96 is not intended to show the precise layout of these elements at any particular time, but illustrates how they could cause irregularity of swamp (and hence seam) margins.

4.4.5 Discussion

Investigation of coal type variations in the Rapahoe Sector strongly suggests that although type characteristics are useful for reconstructing paleoenvironments, they cannot be expected to *directly* indicate seam correlation, due to the influence of rapid lateral changes in depositional environments. Nevertheless, integration of coal type data and sedimentological studies has produced constructive results. Unfortunately, a uniformity of sediment composition appears likely to handicap refinement and testing of correlation models for thick seams in the important southwestern area. However, investigation of the interaction between compositionally distinct western and northeastern sedimentary regimes east of a line through Drillhole 628 and Strongman Mine offers the potential for considerable advances in understanding of detailed paleogeography and seam geometry.

Although it is beyond the scope of the present work to present detailed seam correlation models for the entire Rapahoe Sector, revised sedimentation models have been presented as a basis for future in-depth consideration of seam characteristics, and to provide a framework for interpreting new exploration data as they become available. One point which has not been broached significantly is the relationship between northern and southern parts of the Rapahoe Sector, and specifically the correlation of major seams between the two zones. Absence of a reliable reference horizon is a severe limitation on correlation of these areas, which are tectonically and paleogeographically distinct. It is tempting to suggest that C seam at Strongman Mine, which represents a period of very extensive peat accumulation in the north, may be time-equivalent to the proposed extensive south-western seam. Available information does not refute this suggestion, but the zone of transition between southern and northern depositional areas is marked by rapid changes in sedimentary regime, and the resulting stratigraphic and lithofacies variability prevents definitive correlation between the zones until further drilling takes place in the transitional region.

4.5 BRUNNER COALS AT PIKE RIVER COALFIELD

4.5.1 Introduction

The stratigraphy of Brunner CM at Pike River Coalfield, and paleoenvironmental interpretations based on lithostratigraphic data, are presented in Section 3.4. A reconnaissance petrographic investigation of both Paparoa and Brunner coals from Pike River Coalfield has also been discussed (see 4.2). Section 4.5 now presents a relatively detailed assessment of Pike River Brunner coal petrography and coal properties, and considers their relationship to depositional conditions.

Coal was obtained from CRA as splits from outcrop and drillhole samples. Except for coal petrography and mineral matter studies, all coal analyses used here have been undertaken by CRA. Most outcrop material is moderately to severely weathered and investigations have been limited to proximate analysis, sulphur content, calorific value, and Crucible Swelling Index (CSI). Completion in early 1983 of a 6-hole drilling programme in the eastern, dip-slope region of the coalfield (Fig. 97) provided core of fresh coal, which Pike River Coal Company initially subdivided into plies c.10cm to 1m thick, for which ash, sulphur and CSI were determined. On the basis of this preliminary information, the Company ordered amalgamation of plies into two to four composites per drillhole, and proximate, ultimate and ash constituents analyses and fluidity tests were undertaken. All analytical data were supplied to me. I undertook maceral analyses and reflectance determinations for selected outcrop samples and all drillhole composites.

Stratigraphic columns of the Brunner horizon in Drillholes 1 to 6 are presented in Fig. 98a to f, with ash and sulphur profiles constructed from ply analyses. The upper seam in Drillhole 3 is believed to be a sliver repeated by faulting, derived from the south-east (Appendix 6).

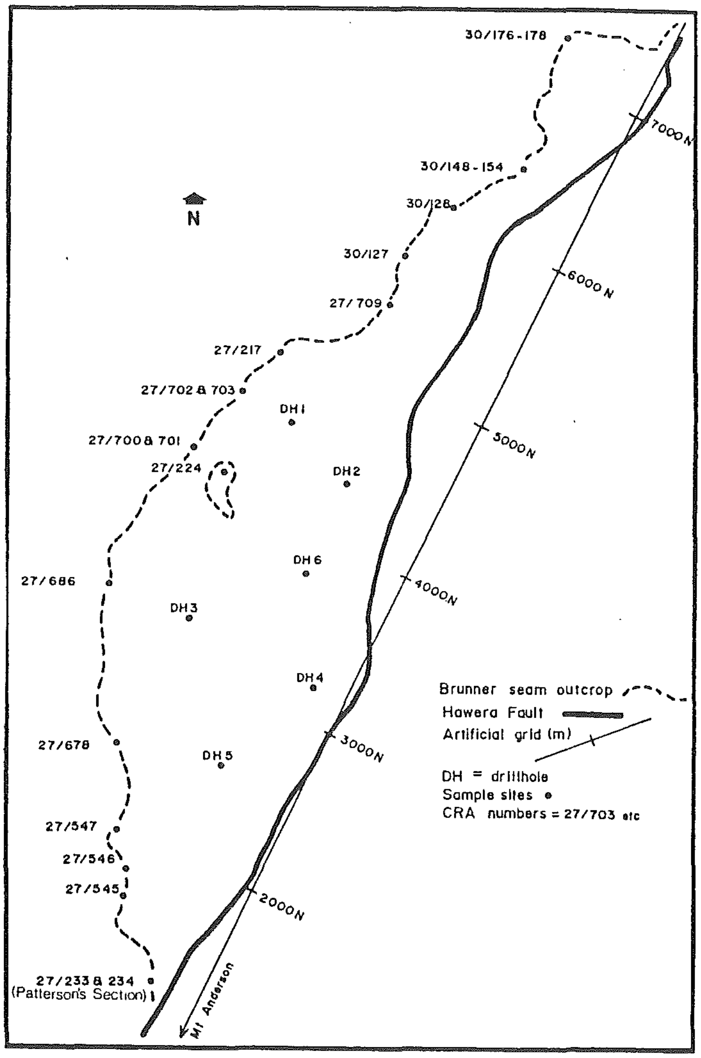


FIGURE 97. Sample and drillhole locations, Pike River Coalfield. The northeast-trending artificial grid is scaled in metres north of Mt Anderson. The closed outcrop at c.4000N is an inlier of coal measures surrounded by Island Sandstone.

4.5.2 Coal Petrology

(a) Results and terminology. Maceral analyses and reflectance measurements are presented together with relevant parts of the CRA results in Table 7 and Figure 99. Maceral analysis values are expressed to $\frac{1}{2}$% instead of the conventional 1%, because some components occur in small amounts. I have defined one variety of vitrinite specifically

Drillhole No.		1	1	1	2	2	2	3	3	3	3	4	4
Composite No.		1	2	3	1	2	3	1	2	3	4	1	2
Coal Res. Ass. No.*		30/791	30/792	30/793	30/926	30/927	30/928	33/003	33/004	33/005	33/006	30/940	30/948
Thickness (m)		0.54	1.61	2.95	0.66	1.74	2.5	2.07	4.29	1.83	4.05	0.8	3.2
Proximate analyses: Moisture	- %	1.1	0.84	1.3	1.3	1.2	1.1	1.1	1.2	1.2	1.2	1.1	0.79
Proximate analyses: Ash	- %	65.0	5.3	2.4	34.5	4.2	3.1	4.8	3.5	3.0	2.7	22.5	3.9
Proximate analyses: Volatile matter	- %	18.8	45.0	43.6	32.0	46.6	43.7	44.7	42.7	43.4	43.4	34.3	43.9
Proximate analyses: Fixed carbon	- %	15.1	48.9	52.7	32.2	48.0	52.1	49.4	52.6	52.4	52.7	42.1	51.4
Calorific value MJ/Kg		8.94	33.43	34.38	21.42	33.84	33.87	33.55	33.72	33.76	33.86	26.86	34.44
Calorific value Btu/lb		3,841	14,370	14,780	9,210	14,550	14,560	14,420	14,500	14,600	14,560	11,550	14,810
Sulphur	- %	7.42	4.3	0.86	8.12	2.79	0.84	3.48	0.82	2.24	0.71	2.98	1.61
Crucible Swelling No.		½	9+	9	4½	8½	9+	9+	9+	9+	9+	8½	9
Volatile matter dmmsf[1]	- %		46.1	44.3		48.1	44.3	46.3	43.3	43.9	43.9		44.7
Ultimate analyses: Carbon dasf	- %		86.4	84.4		86.6	84.3	86.3	84.5	84.9	84.4		85.9
Ultimate analyses: Hydrogen "	- %		6.2	6.1		6.5	6.1	6.3	5.9	5.9	6.0		6.2
Ultimate analyses: Nitrogen "	- %		1.0	1.0		1.2	1.0	1.0	1.0	1.0	0.9		0.9
Ultimate analyses: Oxygen "	- %		6.4	8.5		5.7	8.6	6.4	8.6	8.2	8.7		7.0
Maceral analyses: Desmocollinite	- %		69	64	67	72	67	48	53	60	49	57	61
Telocollinite	- %		6½	7½	4	3	6½	10	11½	14	14	5	10
Vitrodetrinite	- %		7½	11	1	6	10	18½	16	13	19	12	10
Indeterminate Vit.	- %		4	1½	6½	6	2½	-	-	-	-	3	-
Liptodetrinite	- %		3½	8½	½	7	6	10	10½	6½	8	7	10
Resinite	- %		1	½	½	tr	1	1	1½	1	1	2	1
Suberinite	- %		tr	2	tr	1	1	2	2½	tr	1	1	2
Sporinite	- %		tr	-	tr	-	½	-	-	-	-	-	-
Cutinite	- %		-	-	-	-	tr	-	tr	tr	-	-	-
Meta-exudatinite	- %		tr	-	-	-	-	2½	tr	tr	tr	tr	-
Fusinite	- %												
Semifusinite / Inertodetrinite	- %[2]		5½	3	1½	3½	3½	6	3	4	4	4	3
Sclerotinite	- %		tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
Micrinite	- %		tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
Quartz	- %		-	-	)13½	)1	-	tr	½	-	-	5	tr
Clay	- %		-	-			-	tr	-	-	-	1	-
Carbonate	- %		1½	2	tr	tr	2	2	1½	1½	4	2	3
Pyrite	- %		1½	-	5½	½	tr	tr	tr	tr	-	1	tr
$\bar{R}o$ max	- %		0.64	0.71	0.78	0.62	0.73	0.66	0.74	0.71	0.72	0.75	0.74
Fluidity (max. ddm)[3]			>50,000	45,368		>50,000	49,792	>50,000	47,144	49,360	46,692		>50,000
Fluidity range (°C)[4]			120	97		121	92	116	96	104	88		103

TABLE 7: Analytical information for Brunner coal drillhole and outcrop samples, Pike River Coalfield. Most of the data given is relevant to coal type variation.

Notes: 1. Volatile matter corrected for the contribution made by mineral matter and sulphur, using ash constituents data as described in Appendix 8 (where available).

*UC sample No. equivalents appear in Appendix 5.

2. Inertinite in the coals is predominantly inertodetrinite with semifusinite properties, hence both maceral terms are used to refer to this maceral.

3. CRA cannot measure maximum fluidity greater than 50,000 ddm.

4. Due to the limitations of (3), the temperature range from initial softening to eventual resolidification is presented, because this is related to maximum fluidity.

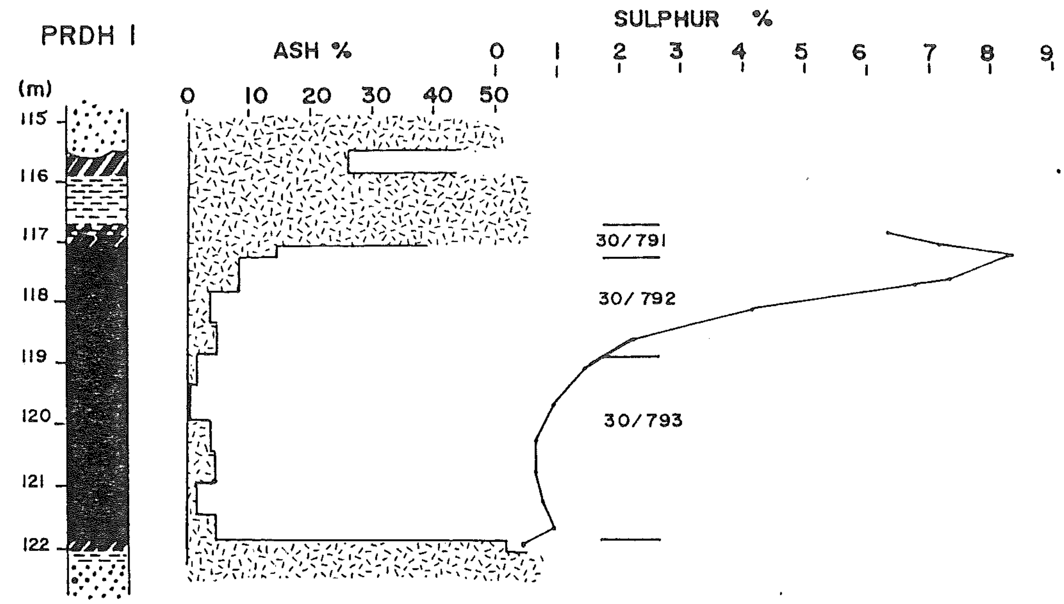
	Drillhole No.		5	5	6	6	6
	Composite No.		1	2	1	2	3
	Coal Res. Ass. No.*		30/966	33/044	30/971	30/985	33/045
	Thickness (m)		3.01	4.60	1.32	3.18	6.75
Proximate analyses	Moisture	- %	0.82	0.94	0.80	0.87	1.2
	Ash	- %	5.5	7.2	7.0	3.1	5.1
	Volatile matter	- %	44.8	43.9	44.5	44.4	41.7
	Fixed carbon	- %	48.9	48.0	47.7	51.6	52.0
	Calorific value MJ/Kg		33.25	33.21	32.56	34.65	33.97
	Calorific value Btu/lb		44,300	14,280	14,000	14,900	14,600
	Sulphur	- %	3.50	4.05	6.32	2.34	0.64
	Crucible Swelling No.		9++	9+	9+	9+	9+
	Volatile matter dmm½sf [1]	- %	45.5	45.8	46.5	45.2	43.7
Ultimate analyses	Carbon dasf	- %	85.9	87.5	87.8	86.8	85.2
	Hydrogen "	- %	6.2	6.4	6.4	6.2	6.2
	Nitrogen "	- %	0.9	0.9	0.9	1.0	0.9
	Oxygen "	- %	7.0	5.2	4.9	6.0	7.7
Maceral analyses	Desmocollinite	- %	58	53	64	60	56
	Telocollinite	- %	11	9	5	8	14
	Vitrodetrinite	- %	14	15½	3	13½	11
	Indeterminate Vit.	- %	-	1	13	-	-
	Liptodetrinite	- %	8	9½	5	9	10
	Resinite	- %	1	1	-	½	½
	Suberinite	- %	1	3	tr	1	1½
	Sporinite	- %	tr	tr	-	-	tr
	Cutinite	- %	-	-	-	-	-
	Meta-exudatinite	- %	1	tr	½	½	1
	Fusinite	- %					
	Semifusinite	- %	3	3½	5½	6	5
	Inertodetrinite	- %					
	Sclerotinite	- %	tr	½	tr	tr	tr
	Micrinite	- %	tr	tr	tr	tr	tr
	Quartz	- %	tr	tr	tr	tr	tr) ½
	Clay	- %	1 tr	-	1	-	tr
	Carbonate	- %	2	3½	1	1	½
	Pyrite	- %	tr	½	2	½	-
	$\bar{R}o$ max	- %	0.72	0.70	0.66	0.69	0.70
	Fluidity (max. ddm) [3]		>50,000	>50,000	>50,000	>50,000	46,732
	Fluidity range (°C) [4]		116	107	120	114	94

TABLE 7 Continued.

Outcrop location		7250N			6450N							5425N	4650N		3200N	1650N
Field sample No.		157	158	159	138	139	140	141	142	143	144	118	111	112	106	89
Coal Res. Ass. No.*		30/176	30/177	30/178	30/148	30/149	30/150	30/151	30/152	30/153	30/154	27/709	27/702	27/703	27/686	27/545
Thickness (m)		1.1	1.1	1.97	0.55	0.70	1.00	2.00	2.00	2.00	2.00	3.40	2.70	5.88	11.1	7.23
Proximate analyses: Moisture	- %	7.4	8.5	5.0	1.7	2.3	1.1	1.4	1.7	1.1	1.4	2.6	1.7	2.0	2.9	1.4
Ash	- %	2.2	1.8	2.6	16.8	32.1	6.3	3.3	1.3	1.6	2.8	3.1	3.0	1.1	6.7	12.6
Volatile matter	- %	38.2	38.6	40.6	40.0	33.9	49.4	45.4	43.5	42.8	45.5	40.8	43.6	42.6	40.3	38.2
Fixed carbon	- %	52.2	51.1	51.8	41.5	31.7	43.2	49.9	53.5	54.8	50.3	53.5	51.7	54.3	50.1	47.8
Calorific value MJ/Kg		28.31	27.52	29.86	27.49	21.32	32.2	33.0	33.43	33.37	33.05	32.26	32.51	33.56	30.48	29.93
Calorific value Btu/lb		12,170	11,830	12,840	11,820	9,170	13,840	14,190	14,370	14,350	14,210	13,870	13,980	14,430	13,100	12,870
Sulphur	- %	0.94	0.50	0.54	6.83	6.91	7.28	3.70	1.27	0.72	0.68	0.82	4.01	1.69	2.18	4.01
Crucible Swelling No.		0	0	1½	9+	4½	9	8½	8	8	8	3	9+	9	4	8½
Volatile matter dmm½sf [1]	- %	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ultimate analyses: Carbon dasf	- %															
Hydrogen "	- %	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Nitrogen "	- %															
Oxygen "	- %															
Maceral analyses: Desmocollinite	- %	74	79	73	65		59	50	40	64½	53	77	74½	64	65	76
Telocollinite	- %	9	10	13	20		8	13	17	15	21	10	11	11	13	6
Vitrodetrinite	- %	2	tr	1	5		15	20	25	6½	11	1	5½	10	8	3
Indeterminate Vit.	- %	nd	nd	nd	nd	"	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Liptodetrinite	- %	10	7	9	5		11	9	6	8	9	6	5	10	9	10
Resinite	- %	tr	-	-	tr		-	tr	tr	tr	1	1	-	-	tr	-
Suberinite	- %	2	2	2	tr		1	1	1	2	2	1	1	1	1	1
Sporinite	- %	-	tr	-	-	"	-	tr	tr	-	-	-	-	-	-	-
Cutinite	- %	-	tr	1	tr		-	tr	tr	tr	tr	-	-	-	-	-
Meta-exudatinite	- %	nd	nd	nd	nd		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Fusinite	- %	-	-	tr	-		-	-	-	-	-	-	-	-	-	tr
Semifusinite	- %	3	2	1	3	"	6	7	10	4	3	4	3	4	4	4
Inertodetrinite	- %	nd	nd	nd	nd		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sclerotinite	- %	nd	nd	nd	nd		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Micrinite	- %	nd	nd	nd	nd		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
R̄o max	- %	nd	0.64	0.64	0.59	"	0.53	0.63	0.67	0.72	0.70	nd	0.64	0.70	0.66	0.68
Fluidity (max. ddm) [3]		nd	nd	nd	nd	"	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Fluidity range (°C) [4]		nd	nd	nd	nd		nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

TABLE 7 Continued.

98a



98b

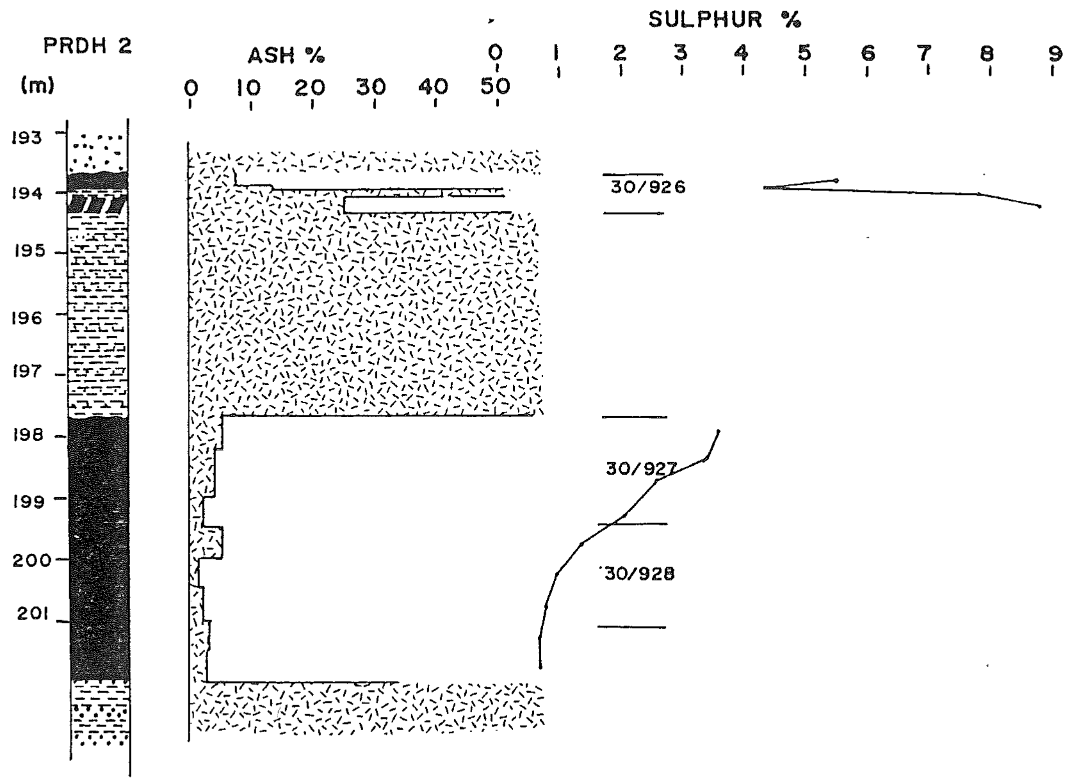


FIGURE 98. Stratigraphic columns of the Brunner horizon in Drillholes 1 to 6 at Pike River Coalfield, with additional ash and sulphur profiles constructed from ply analyses.

FIGURE 98c

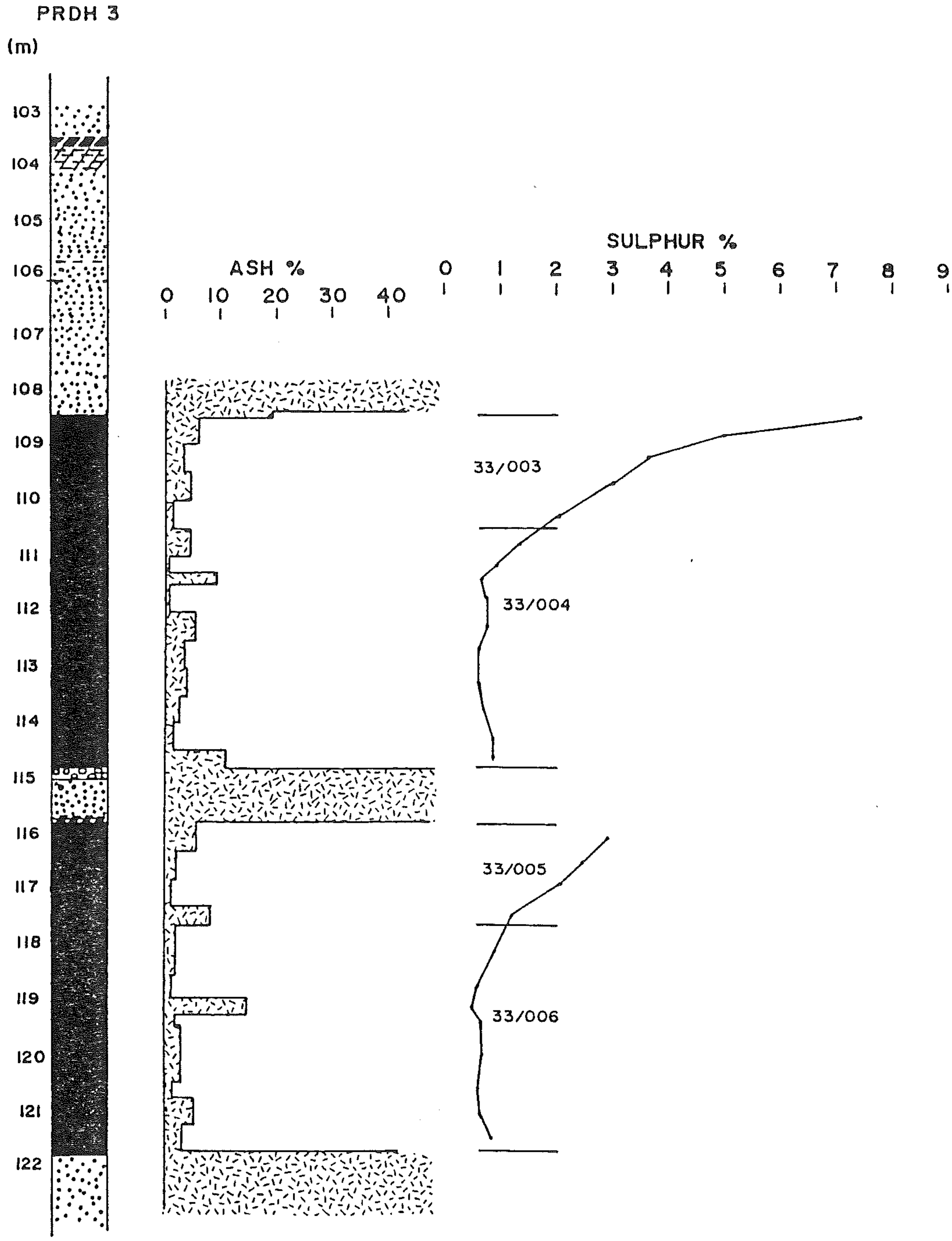

PRDH 3
(m)
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
ASH %
0
10
20
30
40
SULPHUR %
0
1
2
3
4
5
6
7
8
9
33/003
33/004
33/005
33/006

FIGURE 98d

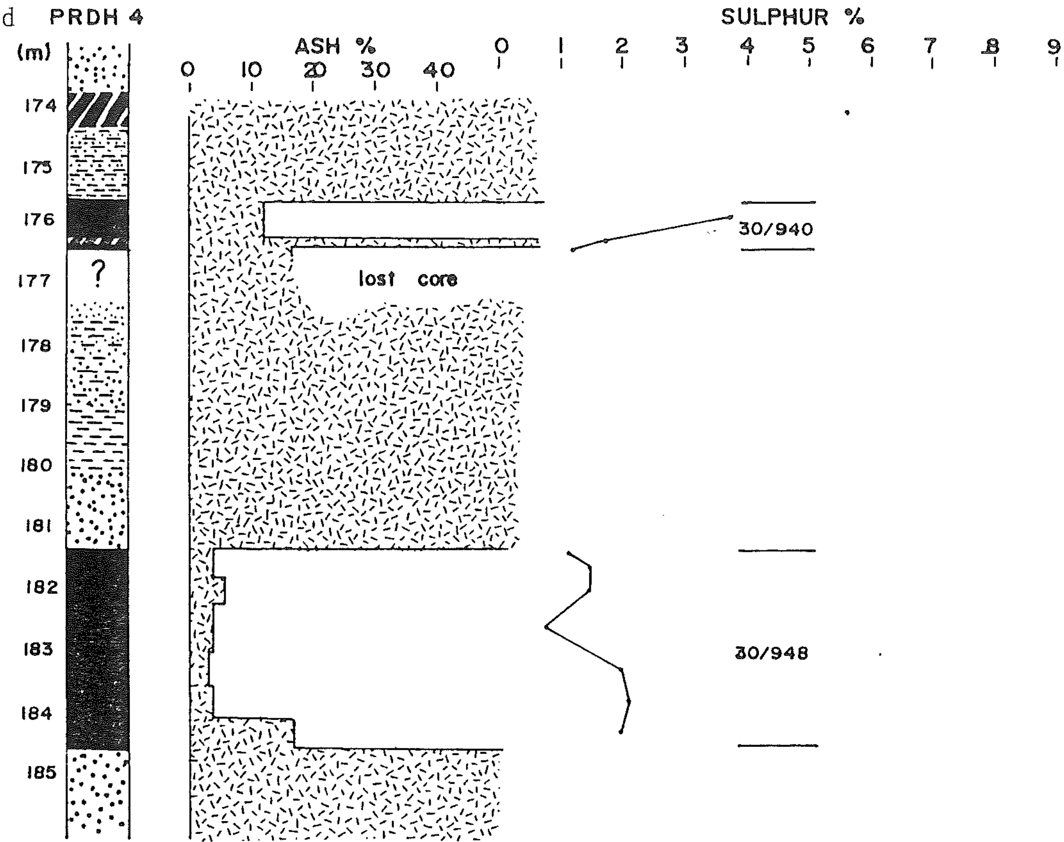


FIGURE 98e

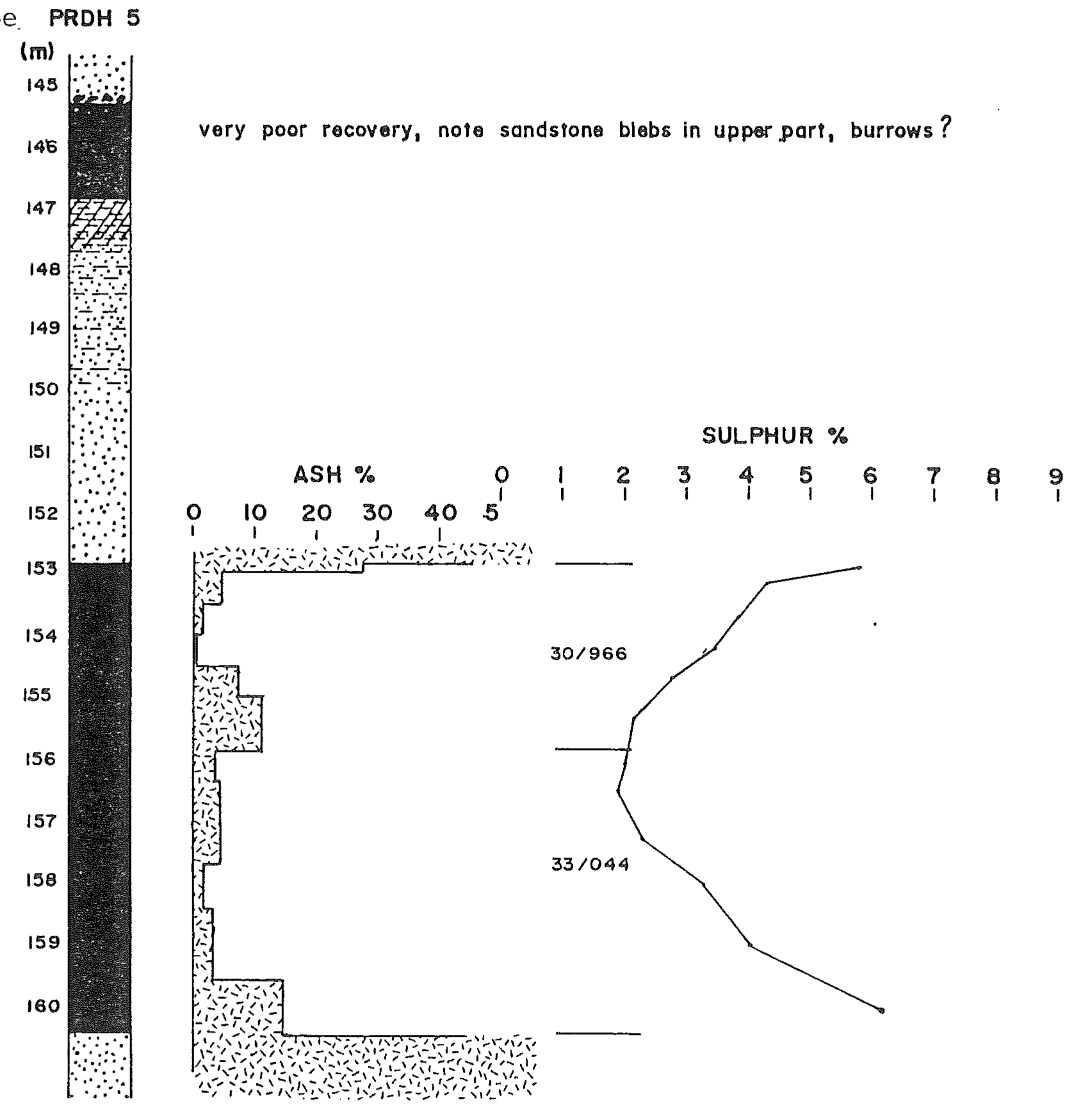
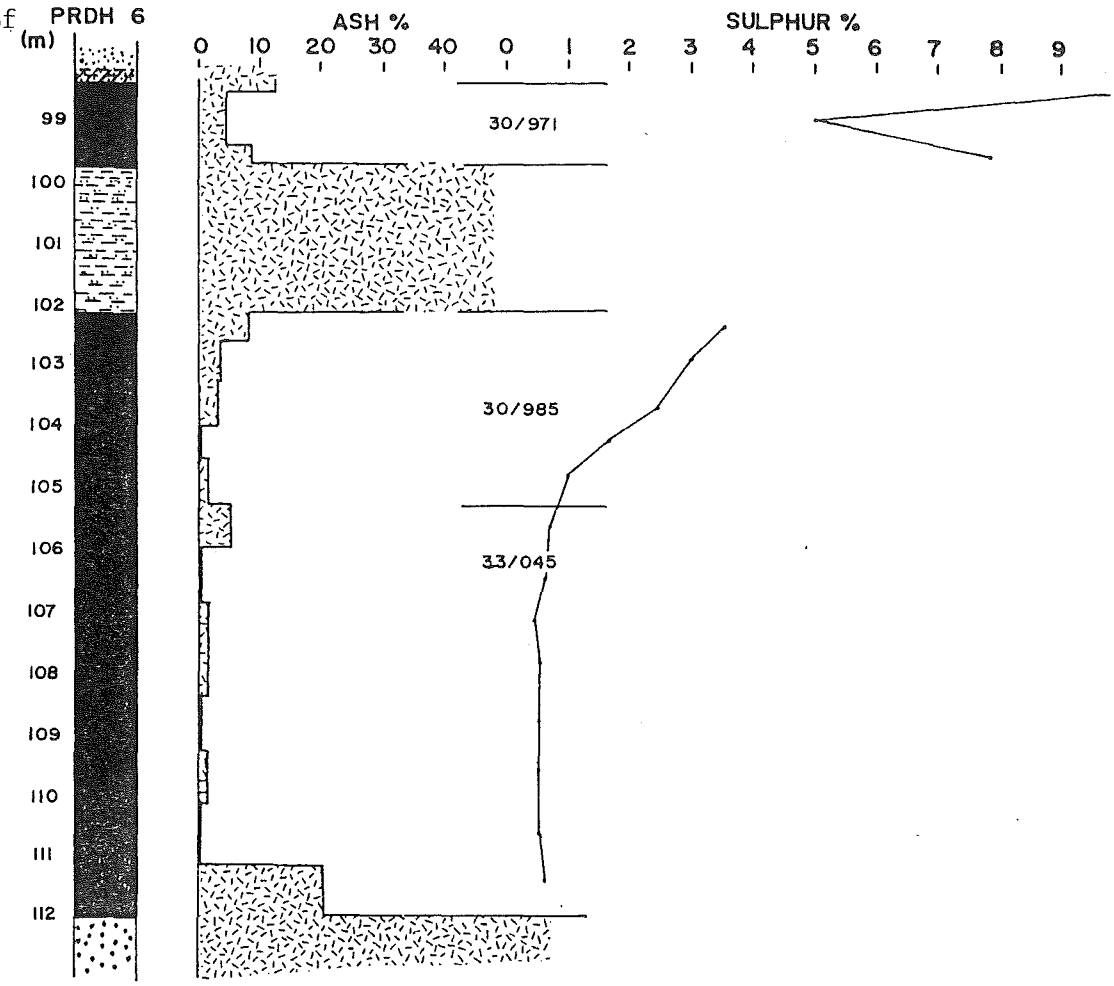


FIGURE
98f



PRDH 6
(m)
99
100
101
102
103
104
105
106
107
108
109
110
111
112
ASH %
0
10
20
30
40
SULPHUR %
0
1
2
3
4
5
6
7
8
9
30/971
30/985
33/045

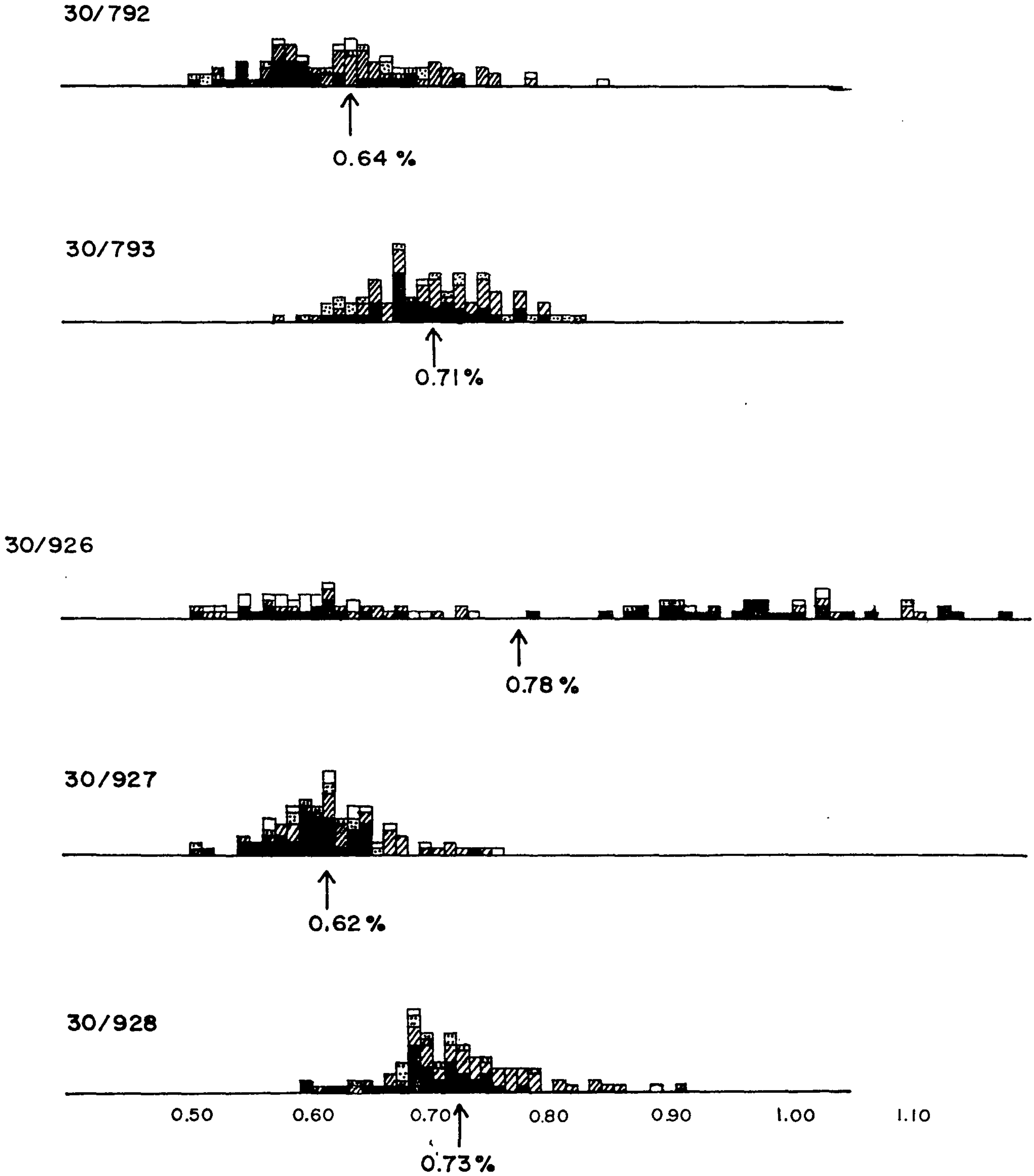


FIGURE 99. Reflectograms for Brunner coal samples from drillholes at Pike River Coalfield. Average values of $\bar{R}o$ max are arrowed.

indeterminate vitrinite
vitrodetrinite
telocollinite
desmocollinite

1 count

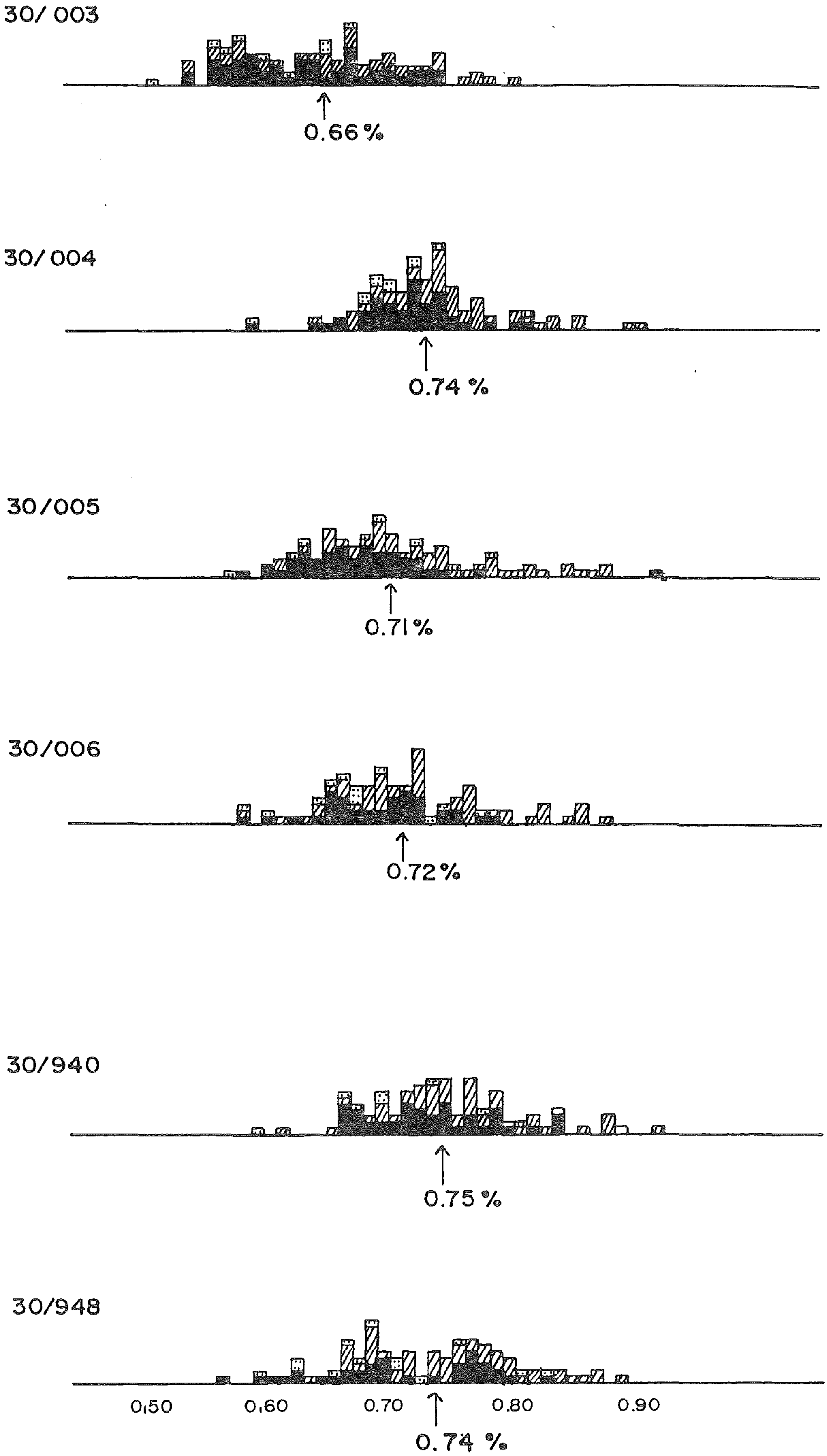


FIGURE 99 Continued.

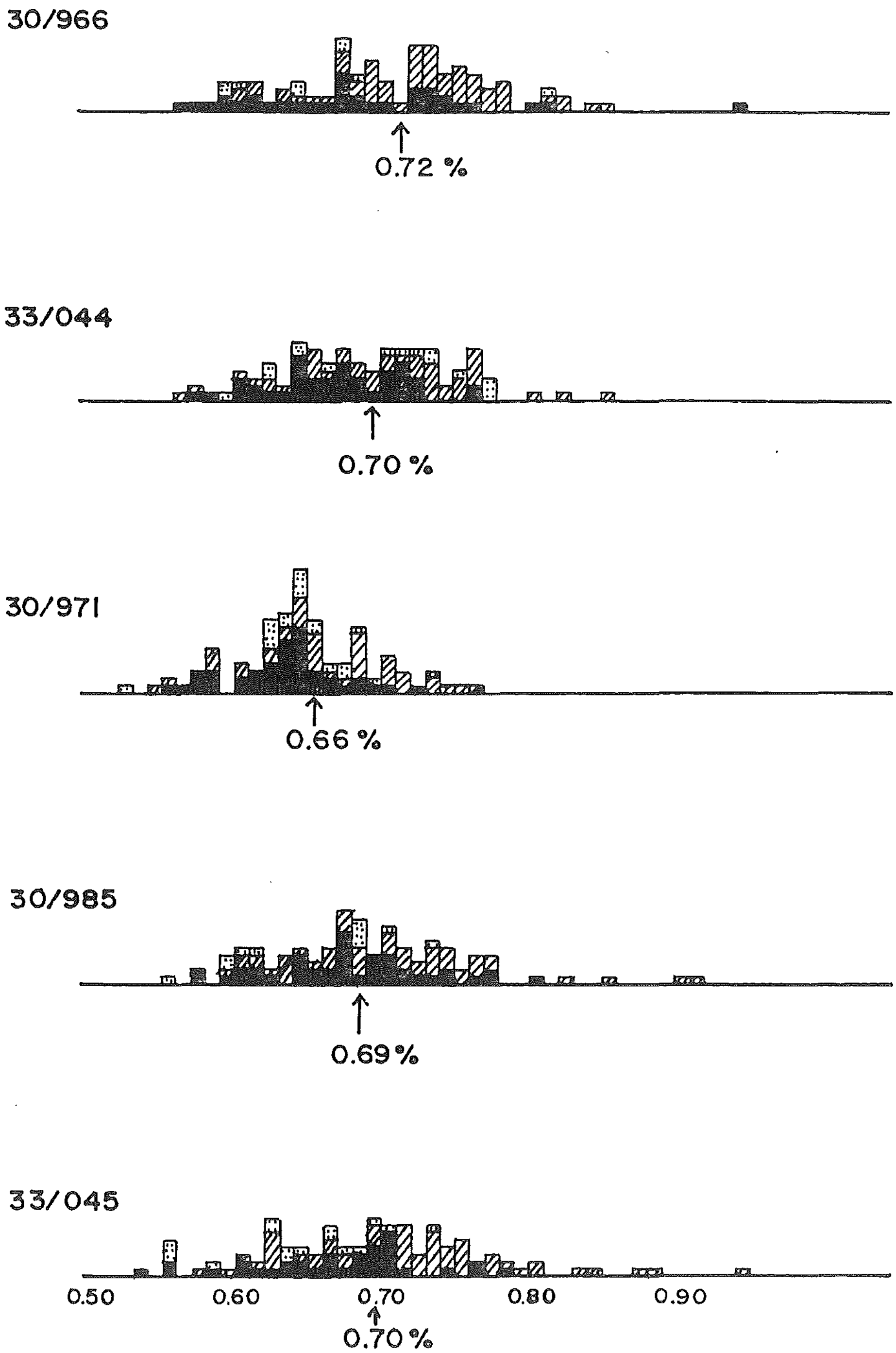


FIGURE 99 Continued.

for Brunner coal studies which is not part of the standard international nomenclature. This is 'indeterminate vitrinite', which consists of telocollinite and desmocollinite which cannot be differentiated. Most commonly this is because the macerals are so homogenous that they are visually identical, or nearly so. In some Brunner coals, desmocollinite tends to be very uniform (Fig. 100), partly due to an extremely sparse content of both mineral matter and macerals other than vitrinite. Telocollinite occurs in forms ranging from distinctly cellular (Fig. 101), to indistinctly cellular (Figs 102 & 103), to featureless, in which form it cannot be distinguished from homogenous desmocollinite. A minor form of indeterminate vitrinite which occurs in Brunner Coals from Pike River Coalfield consists of a mixture of desmocollinite and telocollinite which have been completely homogenised by shearing at an early stage in coalification (Fig. 104a). Conventional maceral analyses might attribute both types of 'indeterminate vitrinite' to desmocollinite, despite a probable telocollinite component, but this practice would distort the petrological data for the sake of convenience while obscuring potentially valuable information. Indeterminate vitrinite occurs in some Brunner coals from Pike River but is mainly abundant in Buller coals (4.6), in which desmocollinite and telocollinite frequently tend to be very featureless.

Inertinite in Brunner coals at Pike River Coalfield is predominantly inertodetrinite with semifusinite reflectance (Fig. 104b), hence both terms are used to refer to this maceral in Table 7. 'Meta-exudatinite' is used to describe a secondary organic material which intruded fractures in the coal during coalification and has a reflectance similar to that of vitrinite.

(b) Discussion. Lateral variations in vitrinite reflectance, exinite, telocollinite, vitrodetrinite, and inertinite are illustrated in Figures 105 to 109, as whole seam (excluding rider) weighted averages, on a mineral matter free basis. The elongate shape of the coalfield, especially in the north, restricts reliable contouring of regional variations in coal properties to a very narrow zone. Lateral trends in various properties and the relationships between them are discussed here, and interpreted in 4.5.4.

FIGURE 100.

Indeterminate vitrinite. Adjacent material (beyond field of view) indicates that the maceral probably consists of desmocollinite in this case. Sample 30/926, drillhole 2, horizontal field 0.25mm.

FIGURE 101.

Distictly cellular (resinous) telocollinite. Sample 33/045, drillhole 6, field 0.25mm.

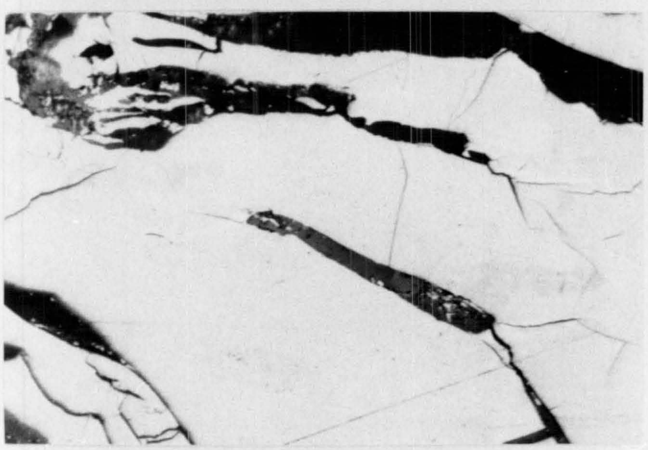


FIGURE 102.

Indistinctly cellular telocollinite. Sample 30/971, drillhole 6, horizontal field 0.25mm.

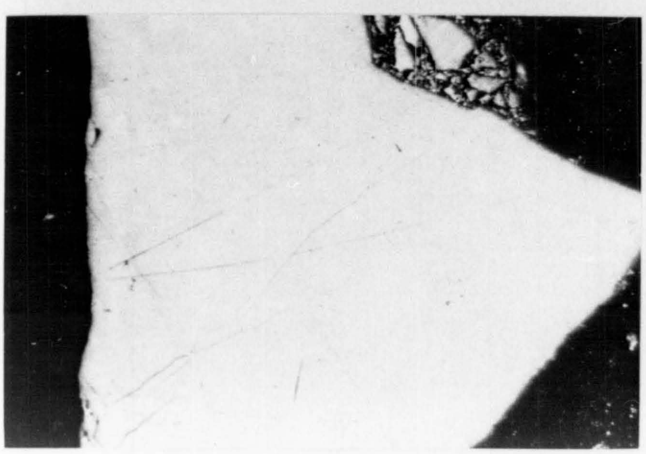


FIGURE 103.

Indistinctly cellular telocollinite. Sample 30/926, drillhole 2, horizontal field 0.25mm.

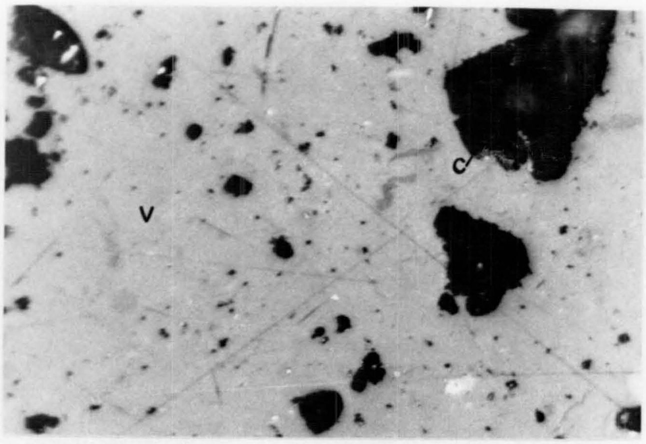


FIGURE 104a.

Indeterminate vitrinite (V) associated with clay (C) formed by the homogenisation of desmocollinite and telocollinite in shear zones. Sample 30/926, drillhole 2, horizontal field 0.25mm.

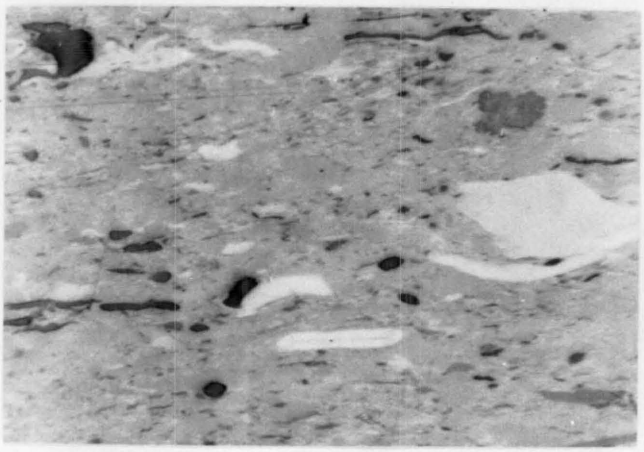


FIGURE 104b.

Inertodetrinite with semifusinite reflectance. Sample 33/004, drillhole 3, horizontal field 0.25mm.

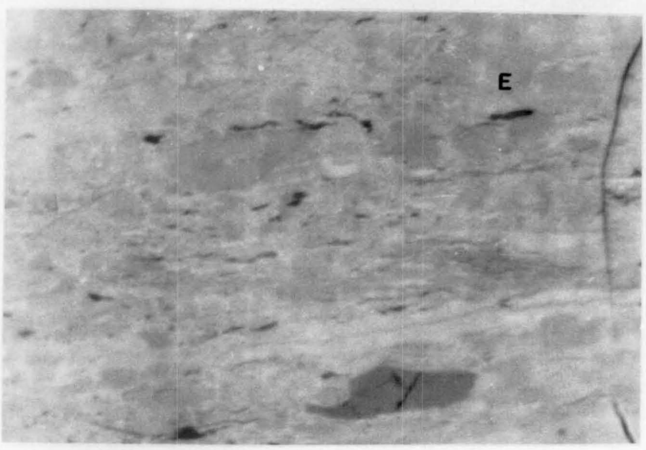


FIGURE 104c.

Coal with sparse exinite (E). Sample 30/926, drillhole 2, field 0.25mm.

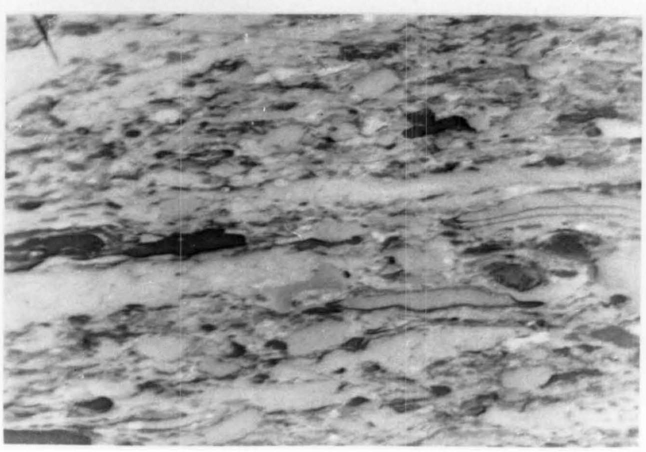


FIGURE 104d.

Coal with abundant exinite (all dark grey material). Sample 33/004, drillhole 6, horizontal field 0.25mm.

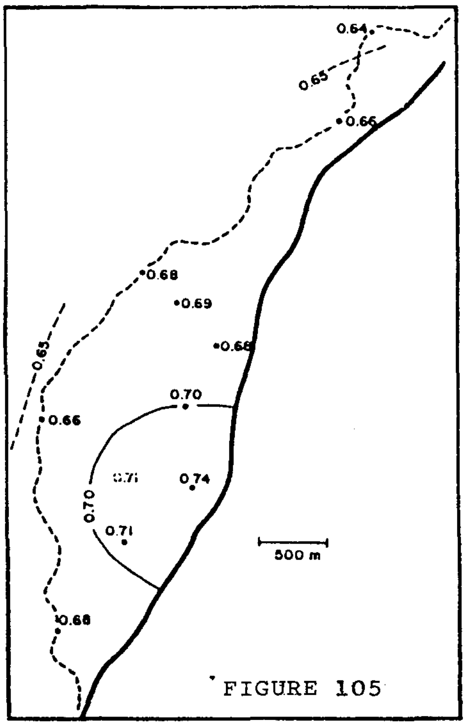


FIGURE 105

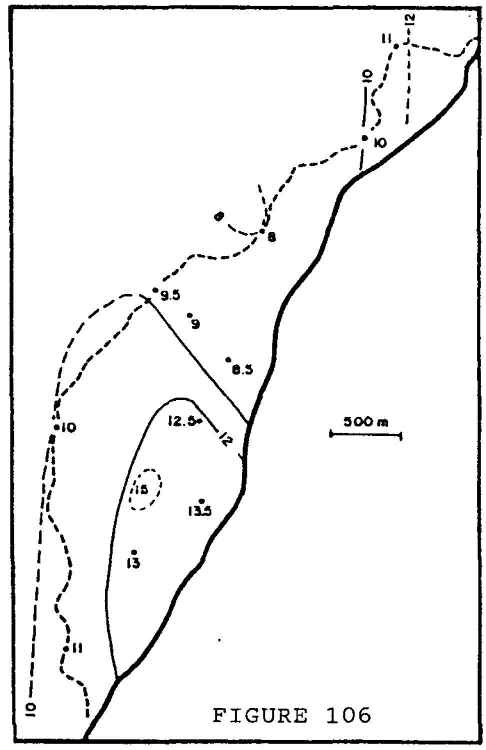


FIGURE 106

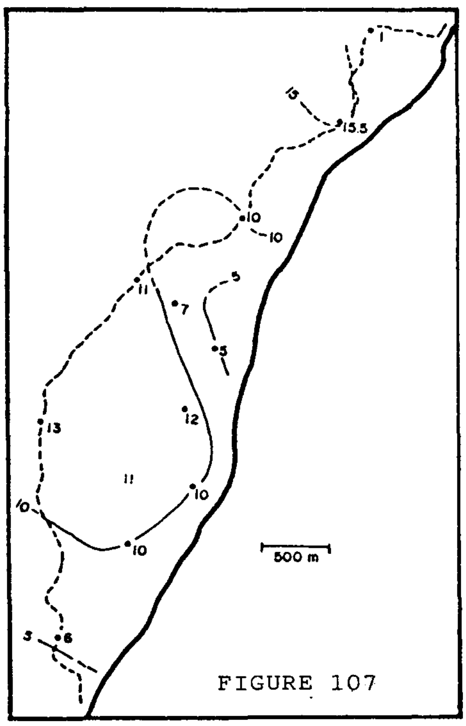


FIGURE 107

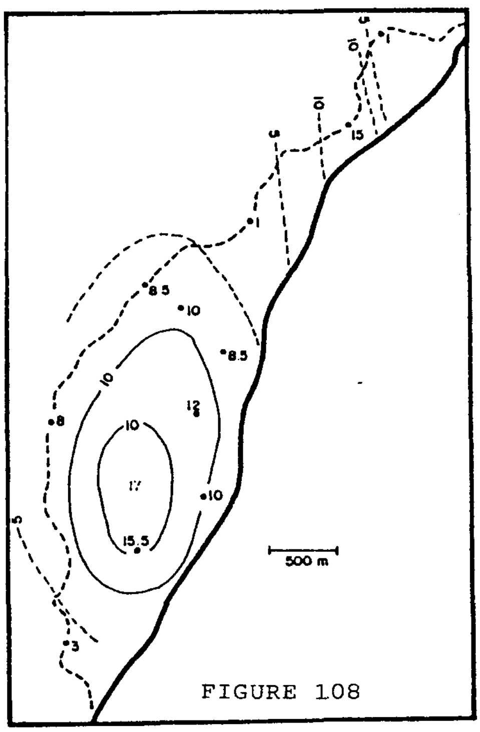


FIGURE 108

FIGURE 105. Lateral variations in vitrinite reflectance (Ro max %), as a whole seam weighted average, excluding the rider seam.

FIGURE 106. Lateral variations in exinite content (%), as a mineral matter free, whole seam weighted average, excluding the rider seam.

FIGURE 107. Lateral variations in telocollinite (%) as a mineral matter free, whole seam weighted average, excluding the rider seam.

FIGURE 108. Lateral variations in vitrodetrinite (%), as a mineral matter free, whole seam weighted average, excluding the rider seam.

In all cases the far northern value may not represent the full seam thickness, due to possible fault complications. 'Broken' numerals represent values for, and inferred original location of, the upper seam in Drillhole 3, believed to have been faulted in from the southeast.

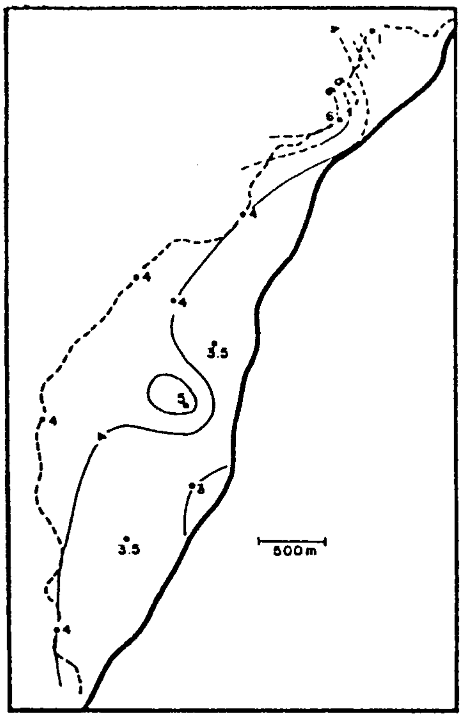


FIGURE 109. Lateral variations in inertinite (%), as a mineral matter free, whole seam weighted average, excluding the rider seam. The far northern value may not represent full seam thickness, due to possible fault complications.

Vitrinite reflectance values range from 0.64% to 0.74% on a whole seam basis, and highest values are clustered in the region of Drillholes 3 to 6 (Fig. 105). Between individual samples, values range from 0.53% to 0.78% . As explained previously (4.2), considerable variation in vitrinite reflectance (greater than 0.4%) can occur between coals of equal rank as a result of coal type influences, and the 0.1% range observed in Figure 105 is considered to result from type rather than rank variation. The pattern of reflectance variation correlates most closely with lateral trends in exinite abundance (Fig. 106), in the sense that exinite percent is highest where reflectance is highest. Exinite ranges from 1% to 15% on an individual sample basis (Fig. 104c & d), and from 8 to 15% on a whole seam basis.

Lateral variations in telocollinite abundance are complex, ranging from 6 to 15% on a whole seam basis (Fig. 107), and from 6 to 21% in the case of individual samples. Comparison of the regional pattern exhibited by telocollinite variation with seam isopachs (Fig. 110) indicates a positive correlation. That is, telocollinite is often must abundant where the seam is thickest. Vitrodetrinite exhibits

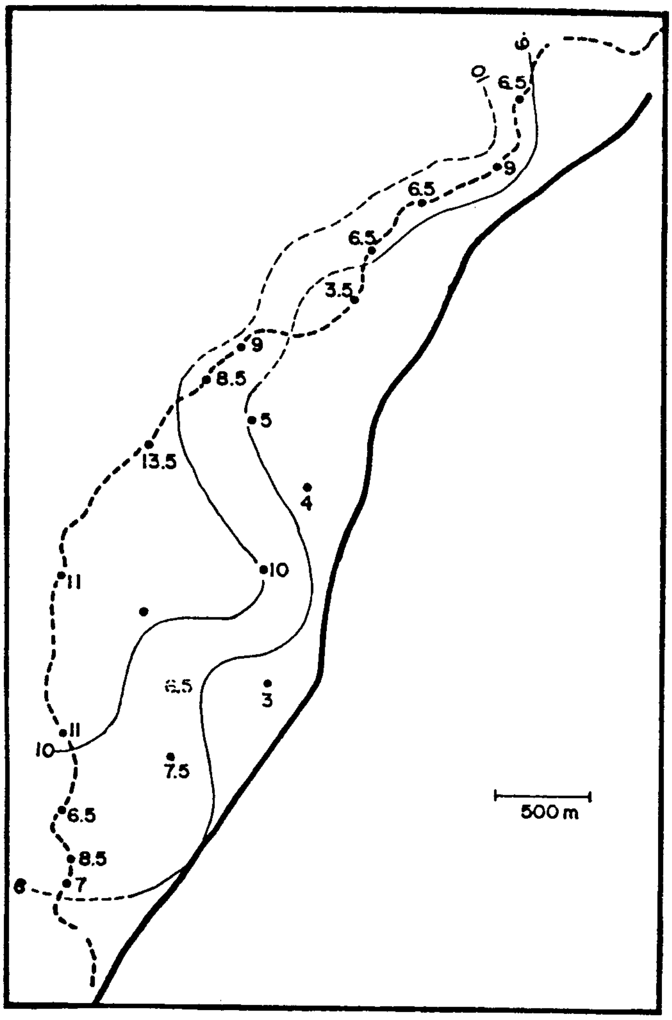


FIGURE 110. Seam isopachs (in metres) excluding sedimentary parting and rider where these can be differentiated. Broken '6.5' represents the thickness and inferred original location of the upper seam in Drillhole 3, believed to have been faulted in from the southeast.

particularly large variations in abundance (Figs 111a & 111b) both on a whole seam basis (1 - 17%, Fig. 108) and between individual samples (tr - 25%, Table 7). Vitrodetrinite occurrence exhibits a weak positive correlation with exinite abundance. Inertinite values range from 1 to 10% between individual samples and from 1 to 6% for the whole seam (Fig. 109), on which basis the maceral exhibits a positive correlation with seam thickness.

In addition to exhibiting regional variations, most coal properties vary within individual seam profiles. Figure 112 illustrates some important vertical trends for Drillholes 1 to 6 and selected seam outcrops. In general, exinite tends to increase in abundance downwards through the main seam, as do reflectance and moisture content. Conversely inertinite, volatile matter (dmm$\frac{1}{2}$sf, Appendix 8), ash (exclusive of secondary minerals, Appendix 9), hydrogen and

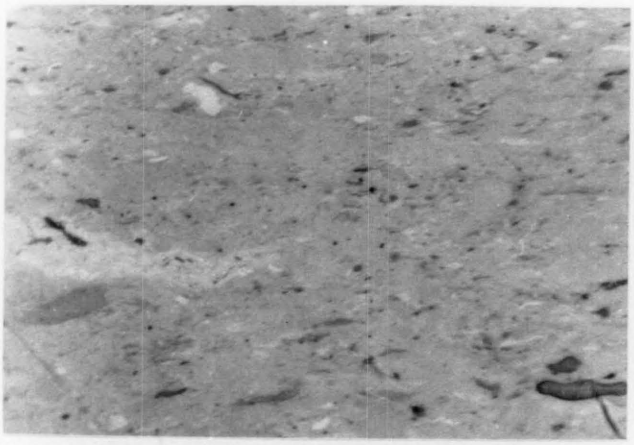


FIGURE 111a.

Coal lacking vitrodetrinite. Sample 30/971, drillhole 6, horizontal field 0.25mm.

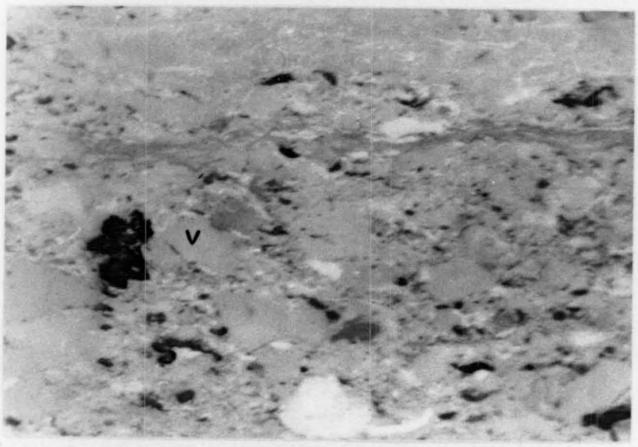


FIGURE 111b.

Coal with abundant vitrodetrinite (V). Sample 30/985, drillhole 6, horizontal field 0.25mm.

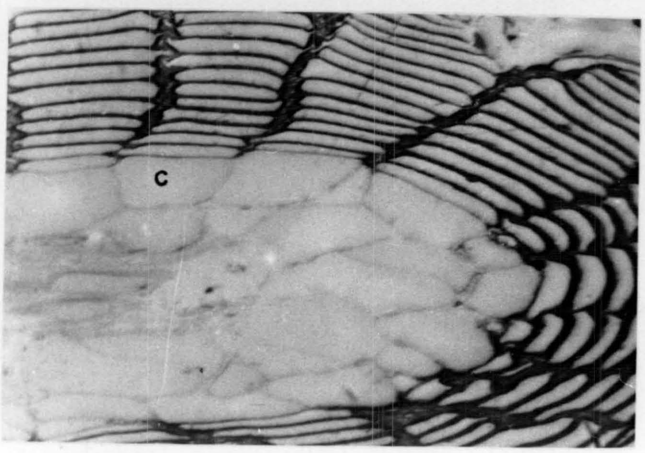


FIGURE 111c.

Stem or root section. Disaggregation of the tissue into isolated cells (C) could provide a source of vitrodetrinite. Sample 33/045, drillhole 6, horizontal field 0.25mm.

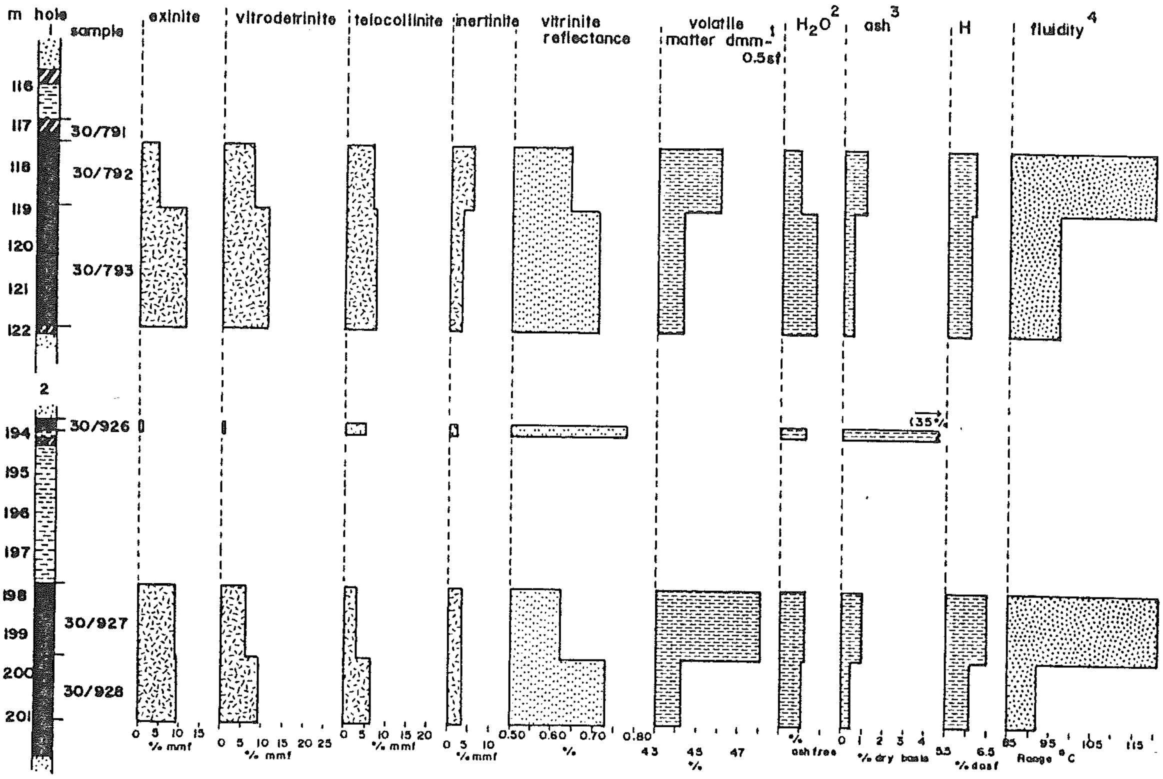


FIGURE 112 Vertical trends in coal properties within seam profiles. mmf = mineral matter free, vitrinite reflectance = $\bar{R}o$ max.

Notes:

1. Volatile matter is corrected for mineral matter and sulphur contributions (Appendix 8).
2. Moisture is expressed on an ash-free basis in the case of of low to moderate ash samples, but in the case of high ash coals the result would be misleadingly low, because mineral matter does in fact contain significant moisture, hence no correction is made in such cases.
3. The ash value presented is 'clastic derived ash', ie., ash exclusive of contributions from authigenic minerals (Appendix 9
4. Because many samples have fluidity in excess of the maximum measurable value (50000ddm), variations in fluidity are here indicated in terms of the temperature range between softening and resolidification, which exhibits a relationship with maximum dial divisions per minute.

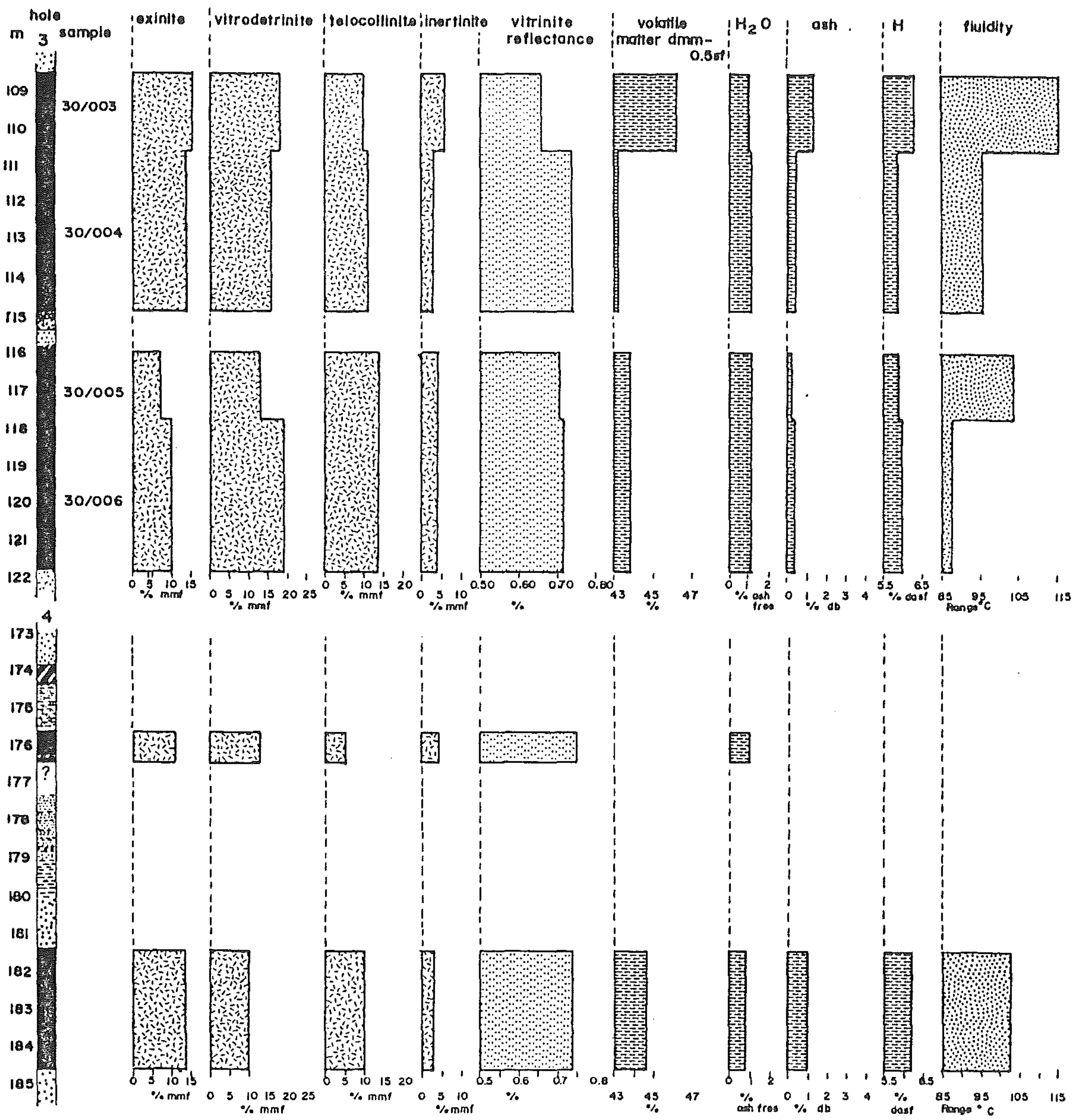


FIGURE 112 Continued.

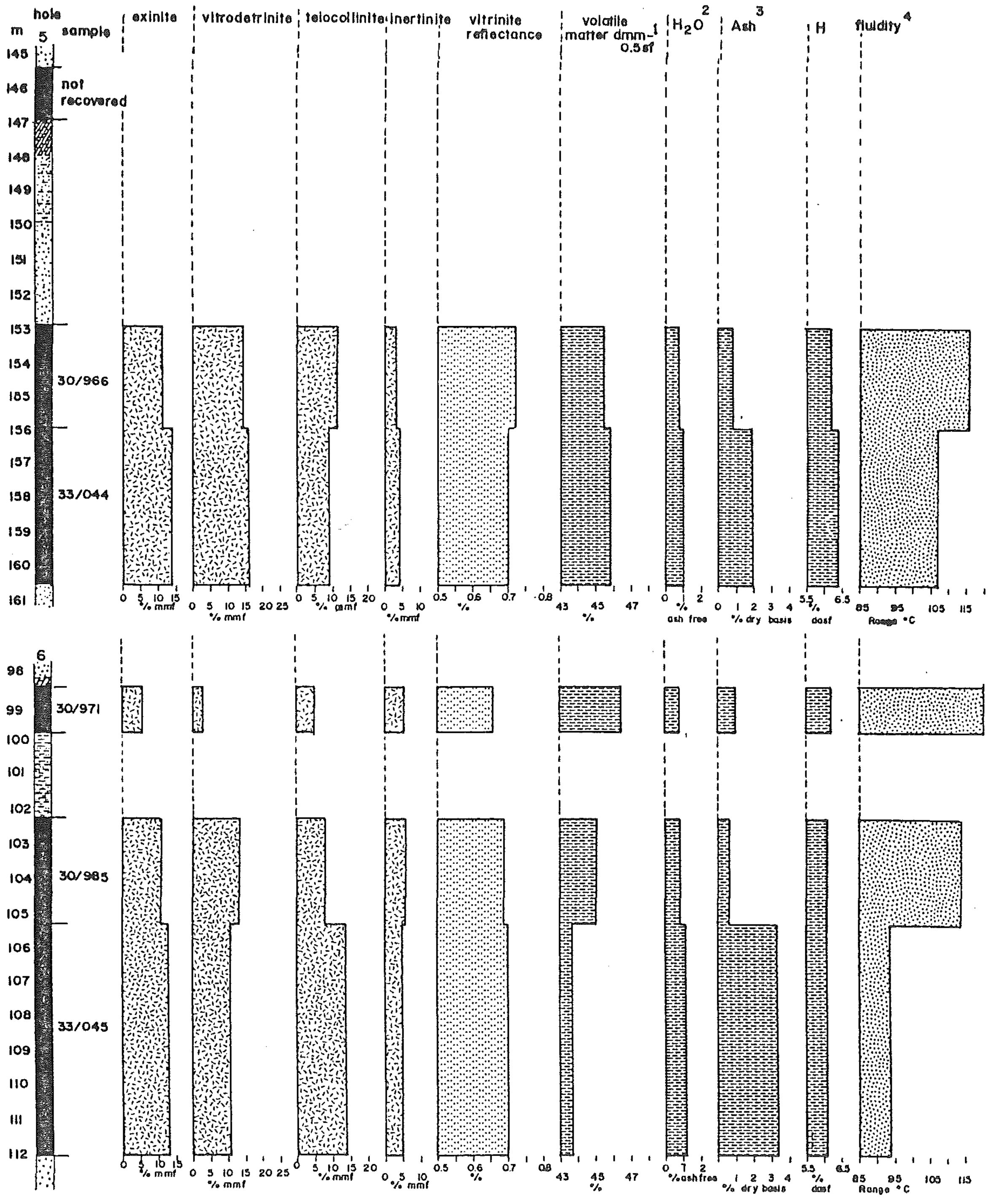
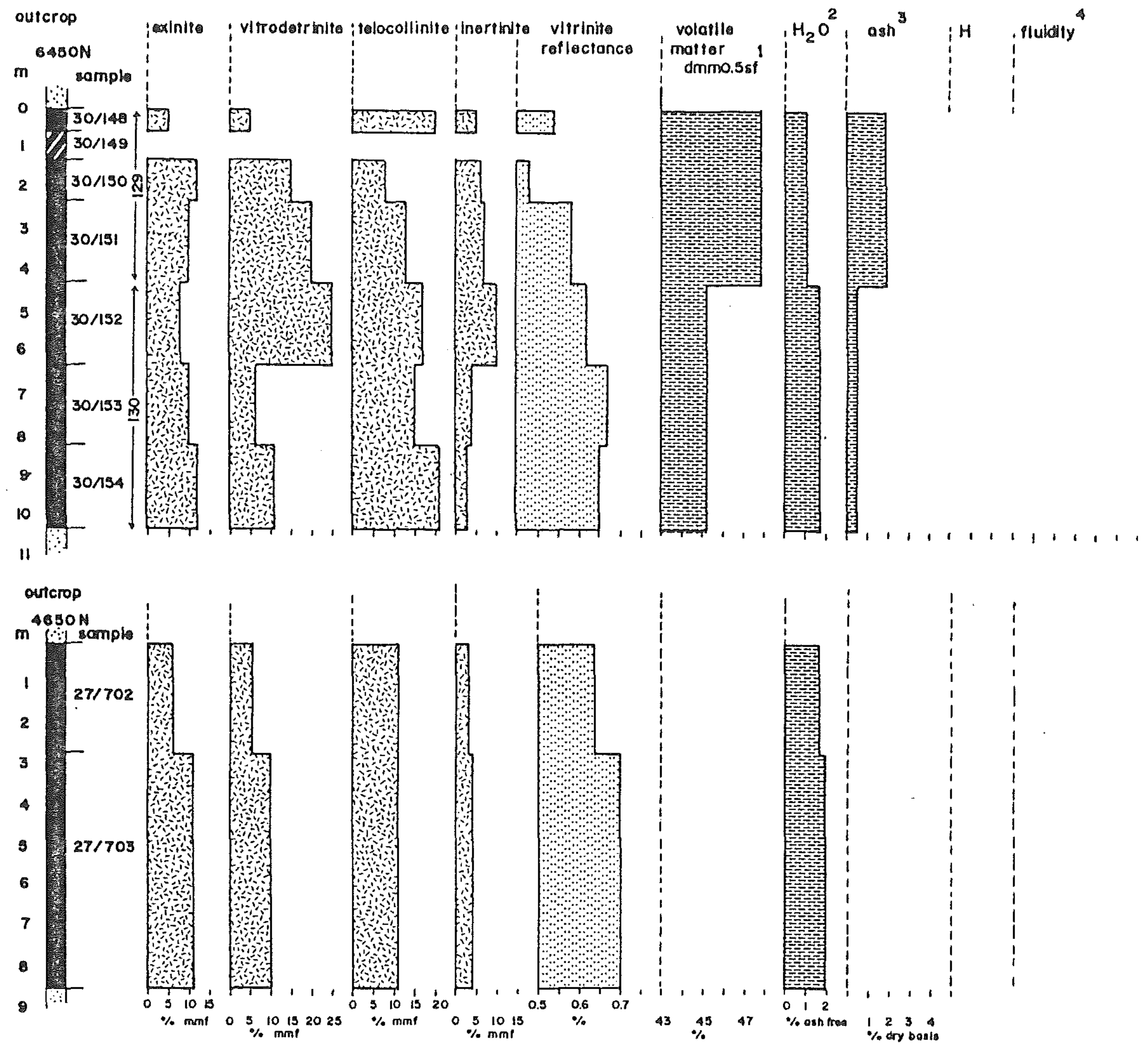


FIGURE 112 Continued.



<u>FIGURE 112</u> Continued.

fluidity tend to decline downwards. Drillholes 1, 2, 3 (in-faulted upper seam) and 6, and main seam outcrops for which petrographic ply analyses are available (4650N and 6450N), exhibit general concordance with these overall trends. The main seam in Drillhole 4 has been analysed as a single sample, hence provides no information on vertical trends, and the lower seam in Drillhole 3 is considered to lack the top third of the seam profile due to faulting. The seam intersection in Drillhole 5 shows little change in properties from roof to floor. Changes which do occur tend to oppose the trends established above, i.e., reflectance decreases slightly downwards instead of increasing, and inertinite, volatile matter, ash and hydrogen tend to increase downwards instead of decreasing.

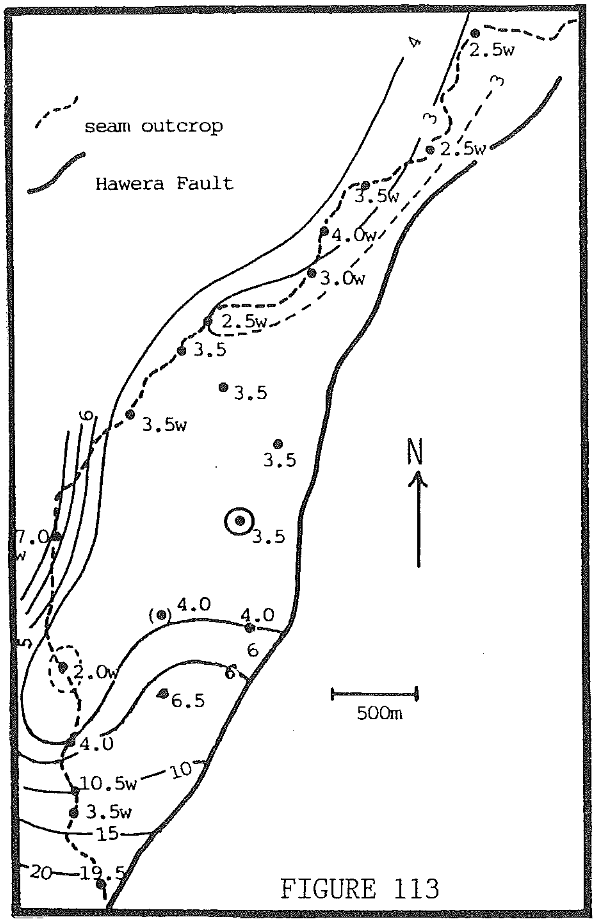
The properties of the rider seam, where sampled (Drillholes 2, 4, & 6), sometimes differ from those of the main seam. In Drillholes 1 and 3 the rider was very thin and dirty, and not sampled. In Drillhole 2 the rider has notably low exinite and vitrodetrinite content, and reflectance is bimodal, with one mode at 0.98% and the other at c. 0.60% giving an average of 0.78% (Fig. 99). A proportion of the sample resembles Webb/Baynes coal from the Buller Coalfield (see 4.6). Exinite and vitrodetrinite contents are again relatively low - compared with the main seam - in the rider of Drillhole 6, although in this case reflectance is unimodal and only 0.66%. The rider in Drillhole 4 is generally similar in character to the main seam. The rider was not recovered from Drillhole 5, but geophysical logs suggest it is moderately clean. In terms of vertical trends, therefore: (1) the rider in Drillhole 6 continues the upward decline in reflectance and increase in volatile matter and fluidity established as typical of the main seam; (2) the rider in Drillhole 4 represents no particular upward trend; and (3) that in Drillhole 2 represents complex trends including some reversal of those which characterise the main seam.

4.5.3 Chemical and physical analyses

(a) Proximate analysis. Proximate analysis measures moisture, ash, volatile matter, and fixed carbon. Moisture (air dried basis) constitutes 0.8 to 1.3% of unweathered, low ash Brunner coal at Pike River Coalfield (Table 7). In weathered samples moisture ranges up to 8%. Moisture variation (ash free basis) in unweathered coal can result from both rank and type variation. In general, given equal rank, coals with relatively high volatile matter have significantly lower moisture than lower volatile coals. This relationship is well demonstrated in 'serial' samples of Pike River Brunner coals (Fig. 112) i.e., samples which are from a common seam intersection and can consequently be regarded as equal in rank. Such samples, e.g., those from Drillhole 6 (Table 7), indicate that the full range of moisture values in unweathered Brunner coals from Pike River Coalfield can be accounted for by type variation.

The ash content of the main seam is usually less than 5% and sometimes less than 1% in the case of individual plies. Lateral variations in main seam ash appear to have no particular relationship with other coal properties, with the exception of a local tendency for volatile matter (dmm½sf, Fig. 114) to decrease as ash decreases. Although this general relationship is considered to have some paleoenvironmental significance (see 4.5.4), a tendency for both ash and volatile matter to be low in outcrop is inferred to result primarily from the effects of weathering. In the case of unweathered coals with ash less than 5% a very high proportion of the mineral matter is carbonate and pyrite, authigenic minerals which are leached out of the coal during weathering. The ash values used in Figures 112 and 113 are estimates of original detrital ash, i.e., ash minus authigenic minerals, as calculated from ash constituents data (Appendix 9). On this basis the coals would be very low ash, consistently less than 2% on a whole seam basis, with individual composites frequently less than 1% ash (N. A. Newman _in press_).

Volatile matter has been demonstrated to vary substantially with changes in coal type (see 4.2, 4.3, 4.4) and, in high volatile bituminous A coals on the West Coast, differences of up to 6% have been estabished between serial samples of equal thermal maturity (see 4.6). Because volatile matter is strongly influenced by contributions from mineral matter and sulphur, some correction is usually needed before the volatile matter of different samples can be meaningfully compared. Values used in Table 7 and Figures 112 and 114 have been corrected to account for the unusually abundant carbonate in the coals and for sulphur. For reasons discussed in Appendix 8, only some of the sulphur is considered to contribute to volatile matter, and correction to a dry, mineral matter and _half_ sulphur free basis (dmm½sf) appears to produce best results. Values are also corrected for the likely affects of weathering, where applicable (Appendix 8).



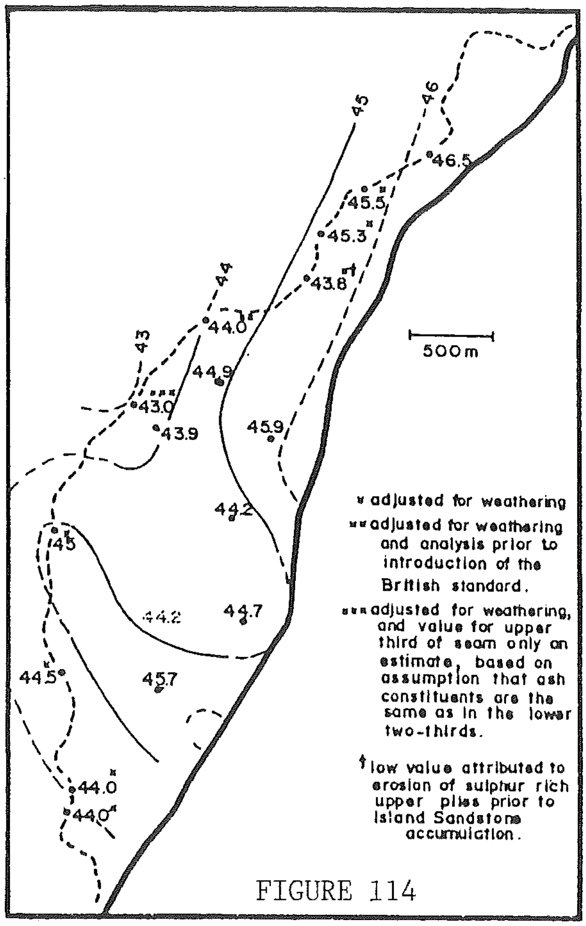


FIGURE 113. Lateral variations in ash content of the Brunner seam, Pike River Coalfield (%, dry basis), as a whole seam weighted average, excluding the rider seam. w = weathered ww = highly weathered. Bracketed (4) represents the ash content and inferred original location of the upper seam in Drillhole 3, believed to have been faulted in from the southeast. Circled 3.5 is the value resulting if the very dirty basal ply in Drillhole 6 is deliberately under-represented (actual whole seam value is 4.5%).

FIGURE 114. Lateral variations in volatile matter yield of the Brunner seam at Piek River Coalfield (dmm$\frac{1}{2}$sf, Appendix 8). Expressed as a whole seam weighted average, excluding the rider seam. Adjustments as explained in the key (also see Appendix 8). Broken '44.2' represents the volatile matter yield and inferred original location of the upper seam in Drillhole 3, believed to have been faulted in from the southeast.

After correction, volatile matter ranges from 43 to 46% for whole seam sections (Fig. 114), and from 43 to 48% between individual samples. Some outcrop values are lower than expected on paleoenvironmental grounds for whole seam data. It is considered likely that the correction employed to counteract the effects of weathering may be insufficient in these cases. Whole seam variations in volatile matter for unweathered coals range from 44.2% (Drillhole 6) to 46.5% (PR129 & 130 at 6450N), which is well within the range exhibited by serial samples from individual sites (e.g., 30/927 versus 30/928 in Drillhole 2; 30/971 versus 33/045 in Drillhole 6) and is consequently considered to result from the influence of lateral type variation.

(b) Sulphur. Sulphur occurs in both pyritic and organic forms in Brunner coals at Pike River Coalfield, and total sulphur values for individual plies range from less than 1% to more than 15%. Extreme concentrations, when present, always occur near the roof, indicating a secondary origin by permeation from above. Secondary enrichment of this nature is considered to be a principal source of sulphur in many high-sulphur New Zealand coals (Suggate 1959). However, there is evidence that some sulphur enrichment of Brunner coals at Pike River may have occurred at the time of peat accumulation. For example, sample 30/150 in the seam section at 6450N (Table 7) has slightly higher sulphur than 30/148 (Fig. 115), which is directly overlain by Island Sandstone. This inversion of the expected sulphur gradient is unlikely to result from dilution due to the higher ash content of 30/150, because high ash samples frequently have high sulphur concentrations (e.g. 30/149 & 30/926, Table 7; 30/322 at 4175N, A=17%, S=15%). In addition to a particularly high sulphur content, 30/150 has very low vitrinite reflectance (0.53%) and abundant framboidal pyrite. It is suggested that a marine influence may be responsible for the unusual characteristics of sample 30/150, and that this influence diminished prior to accumulation of the overlying ply.

There is paleoenvironmental support for marine influence during the life of the swamps, as discussed below (see 4.5.4). Brunner coals at Pike River Coalfield are believed to have accumulated in a back-barrier marginal marine environment, and consistent upward changes in coal properties within the seam (Fig. 112) indicate that the water table gradually rose as peat accumulated (4.5.4). If this gradual flooding resulted in brackish conditions, syndepositional sulphur

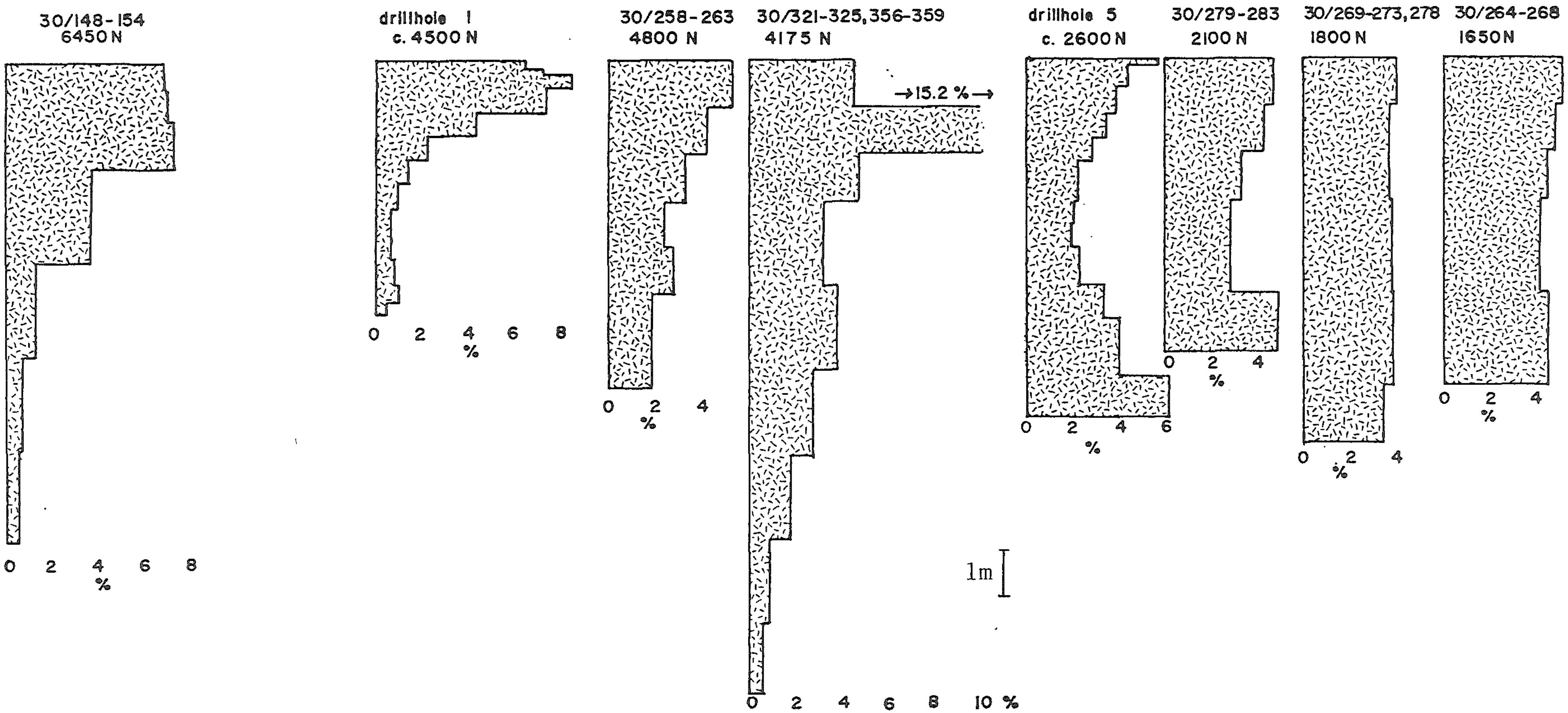


FIGURE 115. Distribution of sulphur within selected profiles of the Brunner seam Pike River Coalfield.

enrichment of the peat is likely to have occurred. It therefore follows that the typical sulphur gradient exhibited by the Brunner seam at Pike River may result both from secondary enrichment by permeation from above and from a generally progressive increase in marine influence during the life of the swamp. The relatively impermeable muddy parting and rider seam above the main seam in Drillholes 1 to 6 could be expected to inhibit secondary sulphur enrichment, and this is consistent with the relatively low *whole seam* sulphur values within Drillholes 1, 2, 3, 4 and 6 (Fig. 116). In view of these constraints, the rather abrupt sulphur enrichment exhibited by uppermost plies in the main seam at most drillholes (Figs 98a to f) probably represents syndepositional (or immediately post depositional) sulphur enrichment under brackish conditions, related to development of the lagoon which interrupted peat accumulation in the area of the drillholes (see 3.4).

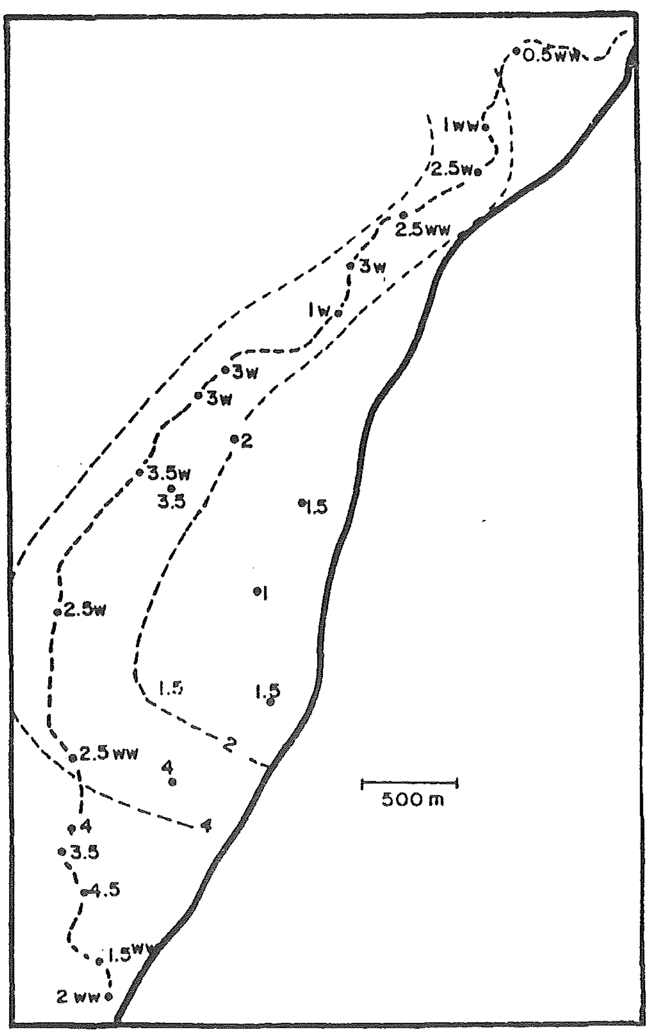


FIGURE 116. Lateral variations in sulphur content of the Brunner seam, Pike River Coalfield (%, dry basis). Expressed as a whole seam weighted average, excluding the rider seam. Broken '1.5' represents the sulphur content and inferred original location of the upper seam in Drillhole 3, believed to have been faulted in from the southeast.
w = weathered ww = highly weathered.

Whole seam sulphur in Drillhole 5 is high compared with values in the other drillholes, and this is largely a consequence of sulphur enrichment of the lower part of the seam (Fig. 98e). Sulphur enrichment of lower plies occurs only in drillholes and outcrop sections south of c. 2600N (Fig. 115). Seam intersections at 1650 and 1800N exhibit high and more or less constant sulphur values throughout the seam, while at 2100N and particularly at Drillhole 5, values increase upwards and downwards away from a relatively low sulphur intermediate zone. All of these sections occur within 1200m of the southern limit of the main seam, where the peat swamp facies is considered to give way to a sandy barrier bar facies (see 3.4.2). Uniformly high sulphur values within seam profiles at 1650 and 1800N are therefore assumed to result from syndepositional enrichment by persistently brackish conditions immediately behind the barrier, and/or lateral secondary enrichment by marine solutions infiltrating from the southern barrier sands via permeable clastic laminae within the coal. In the case of Drillhole 5 and section 2100N, an increase in sulphur towards the floor suggests secondary enrichment via solutions entrained in the underlying sediments. A model of secondary enrichment is illustrated diagrammatically in Fig. 117.

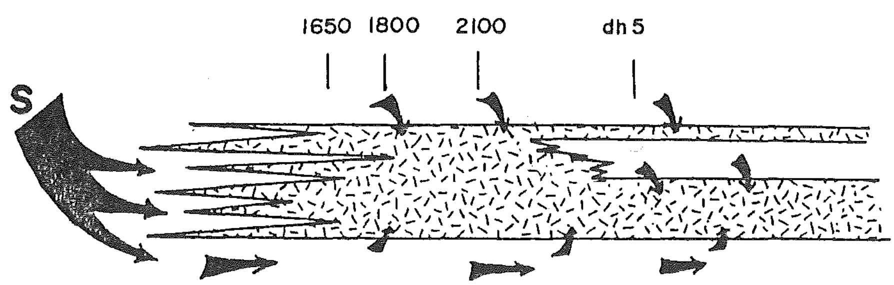


FIGURE 117. Model of secondary enrichment by sulphur carried in solutions migrating along permeable horizons in the Brunner seam, southern Pike River Coalfield.

The fact that the upper half of the main seam in Drillhole 5 exhibits secondary sulphur enrichment whereas in Drillhole 4 it does not, despite the overlying partings being sandy and presumably moderately permeable in both cases, may be a consequence of the proximity of Drillhole 5 to the southern "barrier sand" facies. The sediment parting in Drillholes 1 to 6 probably accumulated in a lagoon connected by tidal channel to a barrier area in the south (see 3.4.2, Fig. 52), and this would result in a permeable sediment path for sulphur-carrying solutions to access the roof of the main seam in Drillhole

5. Presumably Drillhole 4 was too distant from the source of sulphurous groundwater for secondary enrichment to occur. In addition, an interface between a saltwater wedge and freshwater head may have prevented migration of sulphur within sediments from Drillholes 5 to 4. It is also likely that the sediment parting has a diachronous base (see 4.5.5), and the parting/main seam interface may have climbed towards Drillhole 4, thereby protecting the seam from permeating solutions which may not have migrated up-dip.

(c) Ultimate analysis. Of the five elements determined by ultimate analysis, hydrogen is most useful as an indicator of coal type in unweathered coal, although it is also affected by changes in rank. Ultimate analysis of Brunner samples obtained from drillholes at Pike River Coalfield (Table 7) gave hydrogen values ranging from 5.9% to 6.5% dry ash and sulphur free (dasf), corresponding to volatile matter (dmm½sf) of 43.3 and 48.1% respectively, and this variability is considered to result entirely from differences in coal type. Oxygen values vary inversely with hydrogen, ranging from 8.7% to 4.9% (dasf), and both elements are considered to vary in response to the same type changes. Oxygen variation is not favoured as a precise indicator of type change because it is determined by difference, rather than directly, and consequently incorporates the accumulated errors resulting from determination of the other elements. Where significant variation occurs, hydrogen typically increases towards the top of the main seam (Fig. 112), in sympathy with volatile matter and fluidity. These changes are attributed exclusively to variations in vitrinite composition, because vertical trends in exinite and inertinite abundance (4.5.2, Fig. 112) could be expected to oppose the observed trends in hydrogen and volatile matter.

(d) Ash constituents. A useful body of ash constituents data has resulted from comprehensive analysis of drillhole samples. Secondary carbonates are considered to predominate in most samples on the basis of this and supplementary mineralogical information, and N. A. Newman (in press) has developed correction formulae for volatile matter (dmm½sf) and ash minus authigenic minerals; see also Appendices 8 & 9. N. A. Newman's work appears in "Mineral Matter in West Coast Coals", shortly to be published as a report to NZERDC.

(e) Carbonisation behaviour. Carbonisation behaviour, while dependant on coal rank, is also strongly influenced by coal type. For many overseas coking coals, this relationship with type is a simple function of the proportions of inertinite relative to the reactive macerals vitrinite and exinite. In the case of West Coast coals, I consider that the important variable is vitrinite chemistry, which can vary substantially between different coals of the same rank as indicated by serial sample variations in volatile matter, hydrogen, vitrinite reflectance, and fluidity. These changes exhibit no relationship with changes in overall maceral group proportions, and in view of the overwhelming predominance of vitrinite in West Coast coals, major variations in the chemistry and properties of isorank samples are attributed to the vitrinite group alone.

Discussion of carbonisation properties in Pike River coals is here restricted to fluidity of drillhole samples, which ranges from 45,000 to more than 50,000 ddm (dial divisions per minute) for coals with low to moderate ash. High ash coals were not tested. It appears that the CRA equipment will not measure values in excess of 50,000 ddm, and as 8 of the 14 samples tested exceed this maximum value it is difficult to consider trends in carbonisation properties within seams, and to assess relationships between fluidity and other coal properties. For this reason both fluidity and the temperature range from softening to resolidification (°C) are provided in Table 7, and the temperature range only is used in Figure 112. On the basis that the two values exhibit a direct relationship, it is deduced that fluidity increases from bottom to top of the main seam in all cases, and is related directly to hydrogen and volatile matter content and inversely to vitrinite reflectance. These relationships are also observed in other West Coast coals of similar rank for which data are available (see 4.6.4).

Overseas workers have attributed some variations in fluidity to variations in the organic sulphur content of coals, and this approach has recently been applied to West Coast Brunner coals (P. R. Gunn, pers. comm.). However, type gradients typically developed in the Brunner coals in question are such that volatile matter/vitrinite reactivity tend to increase upward in a seam profile, as does sulphur for reasons discussed above. The consequent relationship between sulphur and fluidity is considered to be a result of these parallel trends, but not causative, (unless to a very minor extent). In the seam at Webb/Baynes Block (Buller Coalfield), sulphur is commonly high towards the floor as well as the roof, due to secondary enrichment via permeable floor rocks. In the lower part of the seam, changes to a lower volatile/less reactive type clearly override any influence sulphur may have on fluidity (see 4.6.4).

At Pike River, this relationship is difficult to test, because sulphur is usually high only at the top of a seam, declining steadily downwards, and the one drilled seam intersection which has high sulphur in the lower plies (Drillhole 5) happens to exhibit very little type variation as indicated by vitrinite reflectance, volatile matter, etc. (Table 7). There is unfortunately no fluidity data available to test the relationship between sulphur, fluidity, and other coal properties in the southern seam outcrops which have uniformly high sulphur throughout the seam. Fluidity is so susceptible to weathering that detailed investigation of subtle changes is impossible for outcrop samples.

4.5.4 Paleoenvironmental interpretation: relationship between peat accumulation and coal properties

(a) Introduction. Research on West Coast coals (see 4.2 to 4.6) indicates that oxygen availability, as controlled by water table level, is one of the most important influences on peat character and hence coal properties in both the Brunner and Paparoa Coal Measures. In general, volatile matter and vitrinite reflectance are chiefly affected. Given equal rank, volatile matter tends to be relatively high and reflectance relatively low in coals which accumulated in a heavily waterlogged environment. On the basis of the relatively high vitrinite reflectance and low volatile matter content of some Paparoa M4 seams at Pike River (see 4.3), and the high upper mode of vitrinite reflectance in the Brunner rider seam in Drillhole 2 (Fig. 99), the rank of Pike River coals is considered to be similar to that of eastern Webb/Baynes coal at Buller Coalfield (4.6). If there is such a similarity, most Brunner coal at Pike River Coalfield exhibits very high volatile matter and very low vitrinite reflectance in comparison with that at Webb/Baynes, and these differences must reflect profound paleoenvironmental differences. I suggest that the Pike River examples accumulated in swamps which were much more poorly drained (i.e., wetter, more oxygen deficient), and possibly relatively brackish (i.e., relatively alkaline, favouring bacterial activity and resulting in advanced decomposition of plant tissues despite oxygen deprivation).

(b) Vertical trends in properties within the main seam. Measurements carried out on ply samples of the Pike River Brunner seam demonstrate that vitrinite reflectance almost invariably declines upwards in association with increasing volatile matter, hydrogen and fluidity values (Table 7, Fig. 112). These trends are attributed to gradually rising water levels, and this inference is consistent with changes in other coal properties (see 4.5.2). For example, a tendency for inertinite to increase upward (Drillholes 1,3, 6) is interpreted to result from the introduction of inertodetrinite floated in from peripheral areas during periods of high water. The degree of inertinite increase is frequently very small and it is therefore not surprising that some sections exhibit no significant change (e.g. Drillhole 2). An upward decline in inertinite content in Drillhole 5 is consistent with a reverse of usual trends in volatile matter (i.e., declines upwards) and vitrinite reflectance (increases upwards) and also ash as discussed below. Reversals of usual trends suggest that at Drillhole 5 the main seam accumulated under slightly better drained conditions later in the life of the swamp. In the seam at 6450N (30/148 - 30/154, Fig. 112) inertinite increases upwards in the lower half of the seam but then gradually declines, although other variables exhibit normal trends. It appears likely that the decline corresponds to a shortage of supply of inertodetrinite, probably due to flooding of adjacent areas restricting the generation of oxidised material. This would be consistent with correlation of most upper plies (30/149 - 30/151) with the sediment parting in Drillholes 1 to 6 (see 4.5.5). A decrease in inertinite in the upper third of the seam at 4650N (27/702, 27/703; Fig. 112) may be explained similarly.

Ash derived from clastic sediment (i.e., ash minus authigenic minerals) increases upwards in Drillholes 1, 2 and 3 and would have done so in Drillhole 6 if the very dirty basal ply had been excluded from the lower composite. An upward increase also occurs in section 6450N. Trends in other outcrop sections cannot be determined because in no other case are ash constituents data available for two or more subdivisions of the seam profile. The main seam was also analysed as a single interval in Drillhole 4, hence vertical trends cannot be determined. The main seam in Drillhole 5 exhibits the reverse of normal trends as discussed in the previous paragraph. An upward increase in clastic-derived ash, where observed, is inferred to result from increased flooding of the swamp as the water table rose, with consequential introduction of increasing quantities of clastics in hydraulic suspension and possibly attached to floating vegetation.

Vertical trends in the abundance of exinite, telocollinite and vitrodetrinite vary from section to section rendering a general discussion difficult. The most consistent trend is exhibited by exinite, which frequently declines upwards (Drillholes 1, 2, 5, 6, & Section 4650N), and this may indicate increasingly brackish conditions because exinite precursors are considered to be relatively unstable under conditions of low acidity (Mackowsky 1973).

(c) Lateral trends in properties within the main seam. Regional variations in coal properties (Figs 105-109, 113, 114, & 116) can be discussed in the light of weathering effects and general trends established within individual seam profiles. The tendency for ash values to be lower in outcrop than in drillhole samples is inferred to result entirely from leaching of carbonate and pyrite, which predominate in the case of fresh coals with moderate ash. The apparently high ash content of the main seam at Drillhole 5 reduces to a figure similar to nearby drillholes if compared on a recalculated "clastic-derived-ash" basis (Fig. 112). However, an unusually high whole seam value at 3200N (27/686, A=7%) cannot be attributed to the presence of authigenic minerals, which are low in this sample (N. A. Newman in press), and may result from inclusion of a dirty floor or roof ply, or wash-over from a barrier bar (Fig. 52). Uniformly high ash values south of 2000N are due to generally high levels of clastic impurities throughout the seam, mainly quartz and illite (N. A. Newman, in press), which may represent wash-over into the swamp during storms. This contamination appears to have mainly affected peat up to c.500m behind the inferred barrier bar.

As discussed previously (see 4.5.3), the tendency for whole seam sulphur values to be relatively low in the area of the Drillholes (Fig. 116) is attributed partly to the inhibiting effect of the muddy parting and rider seam on secondary enrichment by permeation from above. Sulphur enrichment may also have occurred syndepositionally, under increasingly brackish conditions late in the life of the swamp. Late peat accumulation is under-represented in the drillholes, due to early flooding of the swamp, and this may have resulted in an additional low-sulphur bias. As previously discussed, high sulphur values in unweathered coals south of c.2600N could be explained both in terms of (1) syndepositional enrichment of peat which accumulated adjacent to a barrier bar in a zone affected by wash-overs; and (2) in terms of lateral secondary enrichment by permeation of solutions along clastic laminae connecting southern portions of the seam with marine sandstones of a barrier facies (see 4.5.3).

Lateral variations in whole seam volatile matter are somewhat complex (Fig. 114), but some of the complications may be a consequence of weathering (see 4.5.3). In general, pre-weathering values for whole seam samples in areas where the mudstone parting is thin or absent are expected to be relatively high, due to inclusion of a substantial proportion of high-volatile coal from the upper part of the seam. Where this portion of the seam is absent due to early flooding of the swamp, the proportionally greater representation of the lower-volatile basal plies may result in a low-volatile bias. This inference is supported by the relatively low volatile matter values of the main seam in Drillholes 3, 4 and 6 (average = 44.5%) compared with values at 5700N, 6075N and 6450N. The anomalously low value at 5425N, where the seam is unusually thin, may result from erosion of high-volatile upper plies prior to accumulation of the Island Sandstone (see 4.5.4(e)).

Lower than expected values at 4875N and 4175N probably result from inadequate adjustment for weathering, in addition to unreliable correction of results of analyses performed prior to introduction of the new British Standard method in the case of 4875N (Appendix 8). At 4175N, unreliable estimation of ash constituents required for correction of volatile matter to a dmm$\frac{1}{2}$sf basis (see notes, Fig. 114) is likely. Relatively high values in Drillholes 1 and 2 compared with Drillholes 3, 4 and 6 are unexpected in view of the thinness of the seam intersections. If peat accumulation had commenced simultaneously at all five drillholes the profiles in Drillholes 1 and 2 could have been anticipated to represent basal, low-volatile coal. However, it is notable that both the coal and the lagoonal parting are thin in Drillholes 1 and 2, hence peat accumulation may have commenced relatively late, resulting in a greater representation of high-volatile peat.

A relatively high volatile matter value for the main seam in Drillhole 5 compared with that in Drillholes 3, 4 and 6 results from a higher than usual value in the lower half of the seam (Table 7), which may be a consequence of peat accumulation in association with a water table which was unusually high for the first half of peat accumulation. This inference is supported by relatively low reflectance values in the lower portion of the seam compared with values in Drillholes 3 and 4, although not in the case of Drillhole 6. Volatile matter values in outcrop south of 2600N could be expected to equal or exceed those in Drillhole 5 on the basis of the paleo-environmental model, and the low actual values appear likely to result from weathering.

The above discussion explains complications in volatile matter data resulting from weathering, inadequate ash constituents information, diachronous peat accumulation, and locally unusual paleoenvironmental conditions. In general, lateral trends in volatile matter values (Table 7 & Fig. 114) support the fundamental inference, from vertical trends (see 4.5.4(b)), that peat became increasingly perhydrous towards the top of the seam due to rising water levels and possibly increasing brackishness during the life of the swamp.

Lateral variations in exinite (Fig. 106) can also largely be explained in terms of changing conditions during the life of the swamp. In general, the highest values are located in the area of Drillholes 4, 5 and 6 where, as previously discussed, the main seam is believed to correspond to relatively early phases of peat accumulation. High exinite values are therefore consistent with the general trend for exinite to increase downwards in the seam, which is tentatively attributed to less brackish conditions prevailing during relatively early stages of peat accumulation. Relatively low exinite valuesin Drillholes 1 and 2 support the concept, based on volatile matter variations, that peat accumulation commenced relatively late at these sites. Outcrop values are also rather low (c. 10%) compared with Drillholes 4, 5 and 6 and this is inferred to result from inclusion of low exinite upper plies which are not present in the drillholes, where the mudstone parting appears in their place. Exinite values in Drillhole 3 are high in the upper seam,believed to have been relocated from the southwest by faulting (Appendix 6), and rather low in the lower seam which is believed to be in-situ. The upper-seam value therefore conforms with the pattern of high values about

Drillholes 4, 5 and 6. No explanation is offered for the lower-seam value, which is unexpectedly depressed.

Lateral variations in vitrinite reflectance accord well with expectations based on trends within seam profiles. High values in the area encompassing Drillholes 3, 4, 5, and 6 are inferred to result from disproportionately high representation of the lower part of the seam in comparison to sections elsewhere which are not truncated by the lagoonal parting. Slightly low values at Drillholes 1 and 2 suggest that peat accumulation was delayed, i.e., that the interval represents wetter (less oxygenated) swamp conditions than prevailed when accumulation was initiated at other drillhole sites to the south.

The theories of seam development applied to volatile matter, vitrinite reflectance and exinite can also be applied to lateral variations in inertinite, telocollinite and vitrodetrinite, but to a relatively limited extent. The latter three macerals exhibit independent patterns of variability and inconsistent relationships with other properties. It appears likely that inertinite and the various vitrinite macerals are complexly influenced by more than one paleoenvironmental factor. A loose but broadly positive correlation between inertinite and seam thickness can probably be attributed to a weak tendency for inertinite to be most abundant in plies which accumulated relatively late (see 4.5.4 (b)). These plies are absent in the drillhole area, due to early flooding of the swamp, and the seam also tends to be relatively thin, hence the correlation between inertinite abundance and seam thickness. The reason for a direct correlation between telocollinite and seam thickness is more obscure, because telocollinite does not exhibit consistent vertical trends in abundance, and is certainly not most abundant in upper plies. A possible explanation is that the maceral is relatively abundant in plies which accumulated very *early*, and that these plies tend to be absent where the seam is relatively thin due to gradual onlap of the swamp onto high areas (see 4.5.5).

More detailed work should help to resolve the paleoenvironmental significance of Brunner coal macerals in general. Some success has been achieved at Webb/Baynes in the Buller Coalfield (see 4.6), although vitrodetrinite appears independent of any known paleoenvironmental influence. This is also the case at Pike River Coalfield, where much of the vitrodetrinite has the character of corpocollinite, i.e., comprising discrete cellular bodies, and comparison of the vitrodetrinite in Figure 111b with interior cells inside a stem or root cross section in Figure 111c suggests that disaggregation of certain plant tissues could be a primary source of vitrodetrinite in Brunner coals at Pike River. If so, vitrodetrinite abundance may depend on the paleoenvironmental preferences of certain plants, and consequently be only indirectly related to actual paleoenvironmental conditions.

(d) The rider seam. Peat swamps were re-established relatively briefly following accumulation of lagoonal sediments, resulting in the rider seam which is clearly developed in most drillholes (Figs 98a - f). This seam is usually dirty and received full analytical coverage only in the case of Drillhole 6, where it was unusually clean. At this location the rider seam properties continue the major vertical trends already established for the main seam, i.e. volatile matter, ash, hydrogen, and fluidity increase upwards and exinite and vitrinite reflectance decline upwards (Fig. 112). Indications are thus of accumulation in wet, possibly brackish conditions. In Drillhole 4 the rider has similar properties to the underlying main seam, as far as can be determined from the data available. Comparison with the Drillhole 6 sample indicates that in Drillhole 4 the rider accumulated in relatively well drained conditions, as indicated by relatively high exinite, reflectance, and moisture values. In Drillhole 2 the rider was thin with ash 35% and petrological examination indicates that the seam resembles Webb/Baynes (Buller Coalfield) samples in having a very low exinite content but frequently high (actually bimodal) reflectance. These characteristics suggest that at some stage the swamp at this location was well drained and relatively well oxygenated. The character of the rider seam clearly varies from place to place in response to lateral variations in swamp conditions, which at some locations (e.g., Drillholes 1 and 3) were entirely unfavourable for peat accumulation.

(e) Post-depositional events. Peat and lagoonal sediments were eventually drowned during a marine transgression which appears to have spread rapidly across the coalfield area. The Brunner seam at 5425N (27/709) is unexpectedly thin (3.5m) and has particularly low whole seam sulphur (0.84%), which is too low to be accounted for by the degree of weathering of the sample. These characteristics suggest that sulphur enrichment of the seam may have largely occurred prior to superimposition of the Island Sandstone, and that Island Sandstone accumulation was preceded by significant erosion of sulphur-rich upper plies in some areas. Furthermore, the extreme sulphur enrichment (up to 15%) of some uppermost plies may indicate that when accumulation of the Brunner seam ceased due to marine transgression, the swamps were flooded by seawater for a period during which little sediment accumulated. Exposure of the peat to sea water is also suggested by intense burrowing of roof coal by marine organisms at some locations. A limited supply of sediment during this period may have resulted from subdued relief in the source areas, which may also have been of limited extent due to marine transgression.

4.5.5 Seam correlation

There appears little doubt that thick Brunner coal exposed in the escarpment and intersected in Drillholes 1 to 6 represents a continuous seam extending over virtually all of Pike River Coalfield. However, precise relationships between seam intersections are obscured by lateral variations in lithostratigraphy and seam thickness. Consideration of ash profiles and vertical variations in coal petrography may assist in seam correlation. For example, ash profiles for seam exposures at 6450N and the inlier at 4140N suggest that mudstone and sandstone bisecting the seam in most drillhole intersections probably correlates, at least in part, with a mineral matter-rich horizon near the top of the seam at some locations where it is not split (Fig. 118). In addition, relatively high volatile matter and low exinite and vitrinite reflectance values in Drillholes 1 and 2, where the seam is thin, suggest a disproportionate representation of peat which was deposited in particularly wet and possibly brackish conditions, typical of mid to late phases of peat accumulation where the seam is thick. This may indicate that peat accumulation commenced later in the vicinity of Drillholes 1 and 2 than, for example, at Drillholes 3, 4, and 6, where values are consistent with initially better-drained conditions. (Indications of relatively poor drainage at Drillhole 5 during early peat accumulation are considered more likely to result from proximity to a barrier bar or lagoonal environment than from a relatively late onset of peat accumulation.)

With the above information, and with reference to seam thickness and the thickness and position of the lagoonal parting, a model of

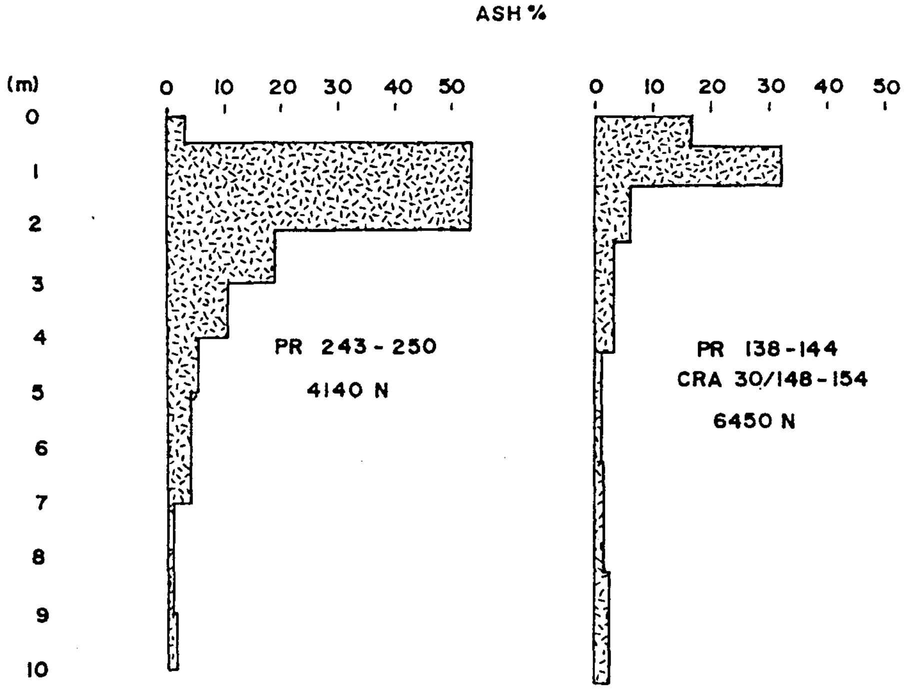


FIGURE 118. Ash profiles for Brunner seam intersections at the inlier (c. 4000N) and 6450N, Pike River Coalfield. High ash zones near the seam roof are considered likely to correlate with the sediment parting which is well developed in the drillholes.

seam correlation has been attempted (Fig. 119). According to this model, the lagoonal parting/main seam interface, and the base of the main seam, are both diachronous. This implies onlap of the swamp onto irregularities in the terrain during initial peat accumulation, and progressive expansion of lagoon waters from south to north later in the life of the swamp. Scouring at 5425N is suggested on the basis of unusually thin coal for a site where lagoonal sediments are absent, and surprisingly low sulphur values in view of the absence of any permeability barrier between coal and overlying marine sediments (see 4.5.4b).

In the absence of more complete information, which would require further drilling and possibly more detailed petrographic examination of a larger number of plies per seam intersection, the correlation model suggested above is very tentative.

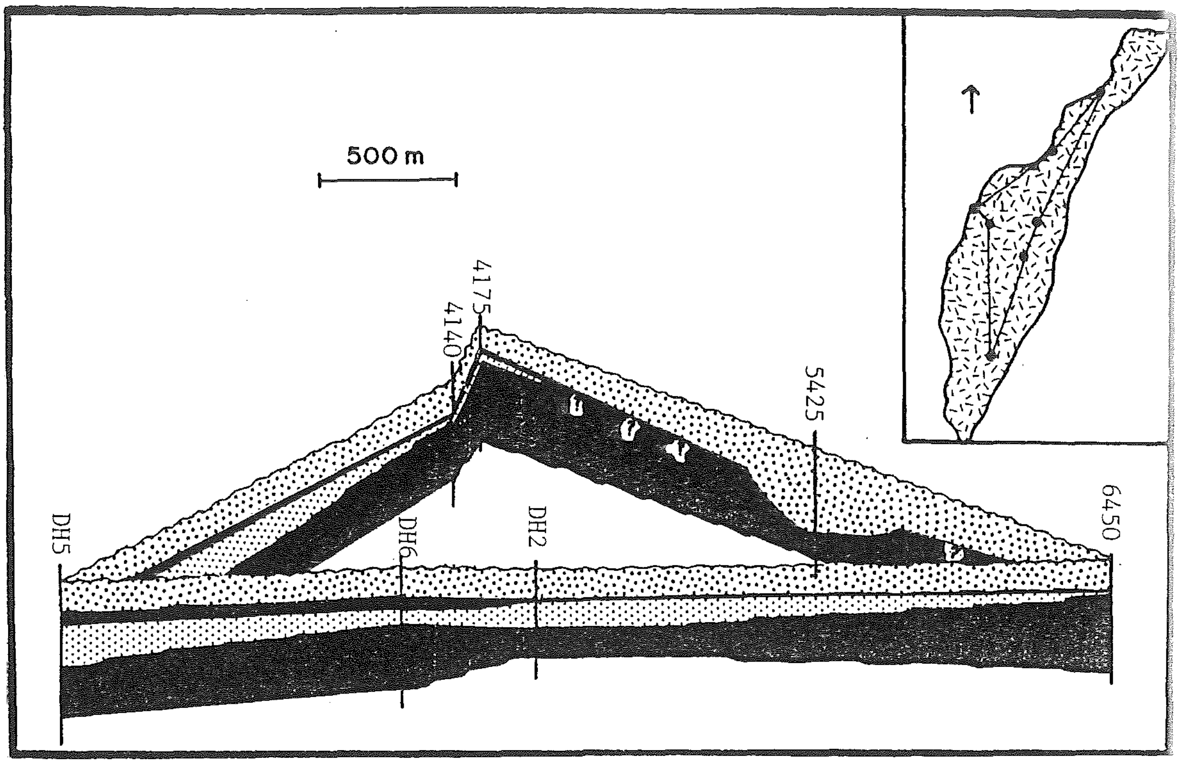


FIGURE 119. Interpretive panel diagram illustrating the Brunner seam and sedimentary parting for seven Pike River Coalfield sections, as shown in the key. Straight lines are presumed time lines and stepped lines represent diachronous surfaces, the steps rising upwards toward younger horizons. Correlations are based mainly on occurrences of sedimentary parting and horizons of dirty coal (both stippled), and consideration of coal type characteristics. Coarse stipple represents Island Sandstone overlying the Brunner horizon.

4.5.6 Summary and Conclusions

Systematic treatment and comparison of petrological and other analytical data for Brunner coals from Pike River Coalfield reveals relationships between paleoenvironments of peat accumulation and coal properties. The coals have very high volatile matter and low vitrinite reflectance in relation to their rank, and are interpreted to have accumulated in poorly drained swamps, probably with some brackish influence. Marginal marine sandstones associated with allochthonous peat in the south resemble Island Sandstone and may represent a barrier bar, and sparsely bioturbated sandstones and mudstones constituting a sediment parting above the main seam in Drillholes 1 to 6 are considered likely to be lagoonal. Autochthonous peat is inferred to have accumulated in back-barrier swamps, and an upward decline in vitrinite reflectance, with a corresponding increase in volatile matter and fluidity, is inferred to result from progressively rising water levels, probably associated with increasing marine influence. These changes are also suggested by variations in abundance of certain macerals, particularly exinite and inertodetrinite. Variations in sulphur values within the seam indicate that sulphur enrichment probably occurred both at the time of peat accumulation, due to marine influence, and after deposition, as a consequence of permeation by sulphur-bearing solutions. Original ash values were very low (usually less than 2%), except near the marginal marine facies in the south, but introduction of authigenic carbonates and pyrite has resulted in substantially higher values (in unweathered coal). It appears likely that the relative abundance of authigenic minerals in the coals will limit, to some extent, the usefulness of density logs for purposes of seam correlation.

A more complete understanding of the reasons for variation in coal properties, many of which influence coal quality, would result from extension of the study which is documented here. Refinement of paleoenvironmental and seam correlation models can be achieved by more intensive examination of vertical and lateral trends in coal properties, and their relationship to inferred paleogeography, particularly if further drilling is undertaken. Careful examination and documentation of exposures which intervene between the unsplit main seam and the marginal marine facies in the south would also provide useful paleoenvironmental information.

4.6 BRUNNER COALS AT WEBB/BAYNES, BULLER COALFIELD

4.6.1 Introduction

Brunner coal in the Stockton area of Buller Coalfield (Fig. 120) is notable for exceptionally low ash values in parts of some seam intersections. During 1983/84, Mines Division funded a programme for assessment of coal from the Webb/Baynes block for specialist uses such as anode carbon manufacture. Drilling and sampling responsibilities were contracted to Applied Geology Associates, who drilled 32 holes (not counting redrills), auger sampled the seam at 9 sites in underground drives, and sampled 4 opencast faces and 4 outcrops (Fig. 121). Sample positions ranged from less than 100m to 200m apart, providing unusually dense data coverage. Approximately half the

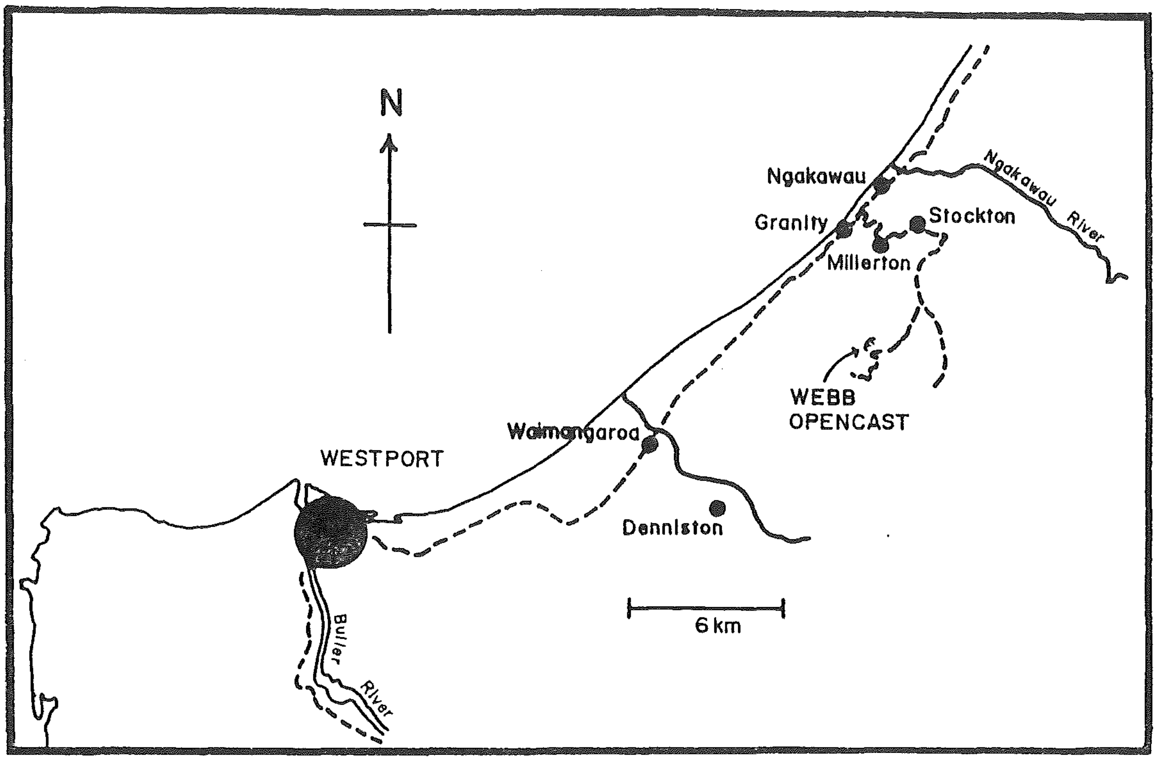


FIGURE 120. Location of Webb/Baynes Block study area (Webb Opencast and environs).

drillholes were cored and the remainder sampled by reverse air circulation percussion drilling, and all were geophysically logged. Ply sample intervals ranged from <20cm to >1m, and these were later amalgamated so that from 1 to 8 composites spanned each seam intersection.

The Webb/Baynes programme provided an excellent opportunity to study relationships between paleoenvironment, coal type and analytical data, using principles derived from work on coals at Greymouth and Pike River Coalfields. Material received by me included descriptive logs of all 49 sample points, ply analysis sheets giving ash, sulphur, free swelling index and washability data, composite analysis sheets giving full proximate, ultimate and ash constituents data (not provided for UG2, OC2, Drillhole 1240), some results of carbonisation tests, and splits of CRA coal composites for petrological purposes. Geophysical logs were not provided; however, ash profiles routinely constructed by the writer using ply analysis data served much the same purpose as a density log, in the case of seam intersections.

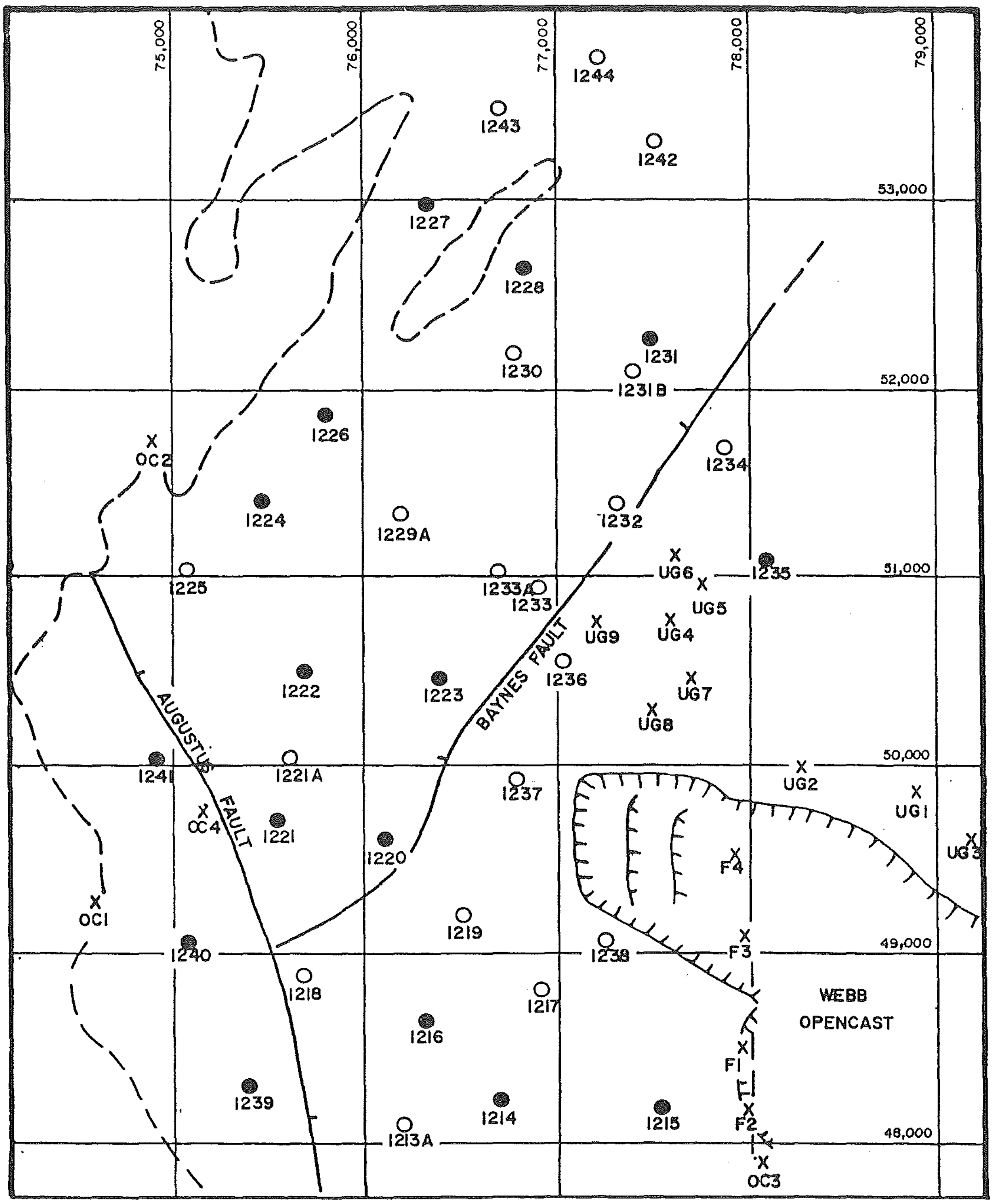


FIGURE 121. Map of Webb/Baynes area showing sample sites. F = face sample, UG = sample from underground drive, OC = outcrop sample, open circles = reverse circulation sampled drillholes, filled circles = cored drillholes. Grid interval in feet.

4.6.2 Stratigraphy, sedimentology, and seam thickness

(a) Data processing. I transformed Applied Geology Associates' descriptive drill logs into my own style of graphic sedimentological log at a scale of 1cm = 2m, coloured to distinguish sediments finer than sand sized from those which are sand sized and coarser. Ply analysis sheets were used in the construction of graphic seam profiles at a scale of 1cm = 1m, illustrating ash, sulphur and swelling number distribution within each seam intersection. These draft figures were working tools for data assimilation and interpretation and are not reproduced here except for 2 examples of the technique (Figs 122 & 123). A complete set is held in the Geology Department, University of Canterbury.

(b) Discussion. Lithological borehole logs show that the coal measures consist of 2 main sedimentary facies in addition to coal. The upper part of the succession is typically dominated by granular coarse sandstone which extends down to the seam in some places and is separated from it elsewhere by a finer interval dominated by muddy sediments which are occasionally bioturbated (Fig. 124). The coarse facies is distinctively fluvial and the muddy facies is suggestive of a marginal marine environment. In some drillholes the two lithofacies are not easily differentiated, in which case a range of values is given on the map showing thickness of the muddy facies (Fig. 125). This facies map demonstrates a generally inverse relationship with seam isopachs (Fig. 126), i.e., the seam is thin where the muddy facies is thick, and vice versa. Regional trends in this relationship are inferred to have paleogeographic significance. The simplest interpretation is that peat accumulation commenced at more or less the same time in most parts of the area under consideration, and that subsidence resulted in a gradual rise in water level which progressively inundated relatively low-lying areas. Drowning of the peat was followed by accumulation of mainly fine sediments contemporaneous with persistent peat accumulation on higher ground (Figs 127a and 128). This sequence of events and the sediment characteristics are consistent with sedimentation in, for example, a lagoonal or interdistributary bay setting. The coarse upper lithofacies represents the influx of a fluvial system into the area, terminating both peat accumulation, where the swamp still persisted, and accumulation of fine muddy sediments elsewhere (Fig. 127b). Some modification of seam thickness occurred due to local erosion of the

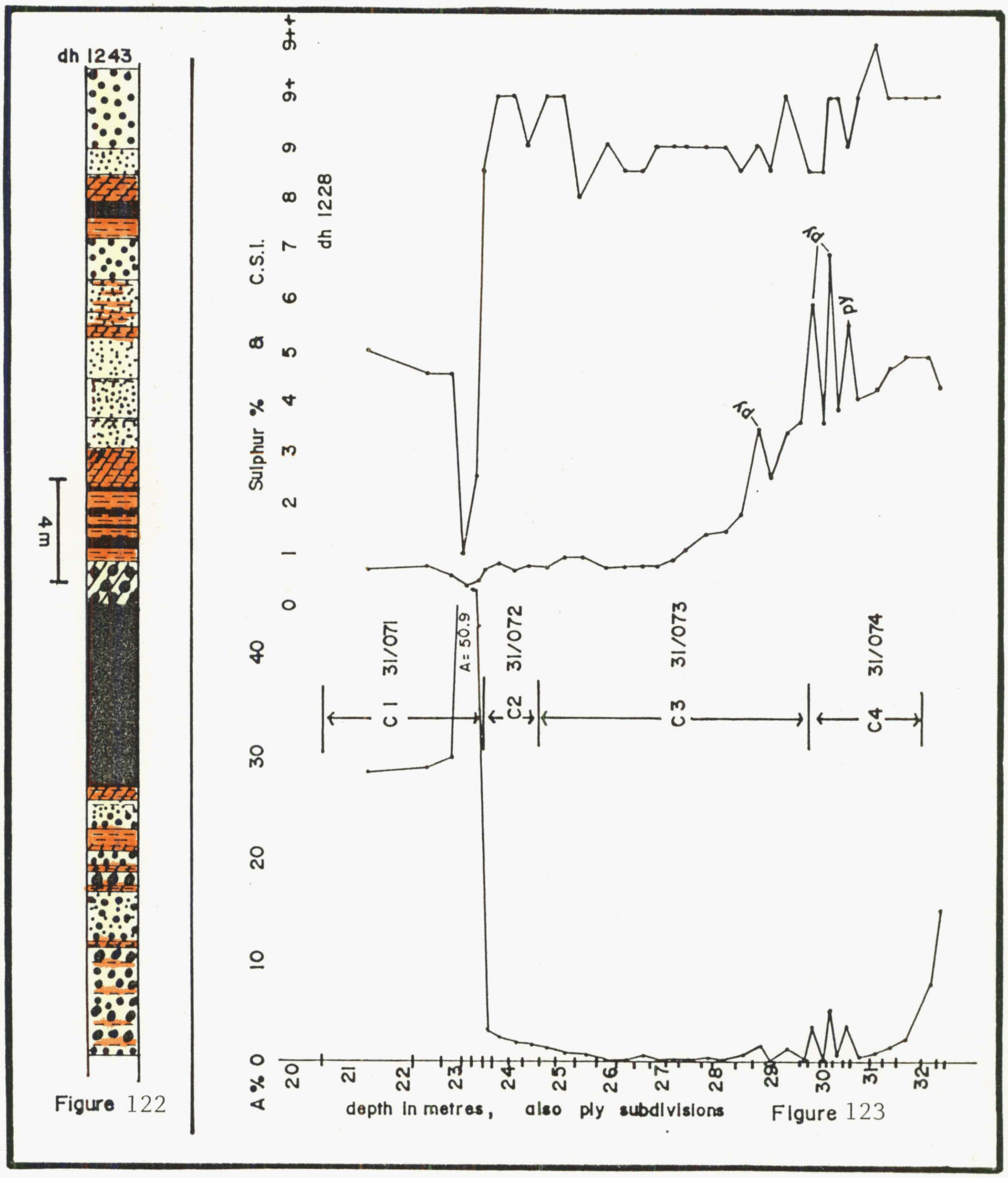


FIGURE 122. Example of coloured graphic sedimentological log prepared for all drillholes; yellow = sandstones orange = mudstones.

FIGURE 123. Example of graphic seam profile prepared for all sample sites.

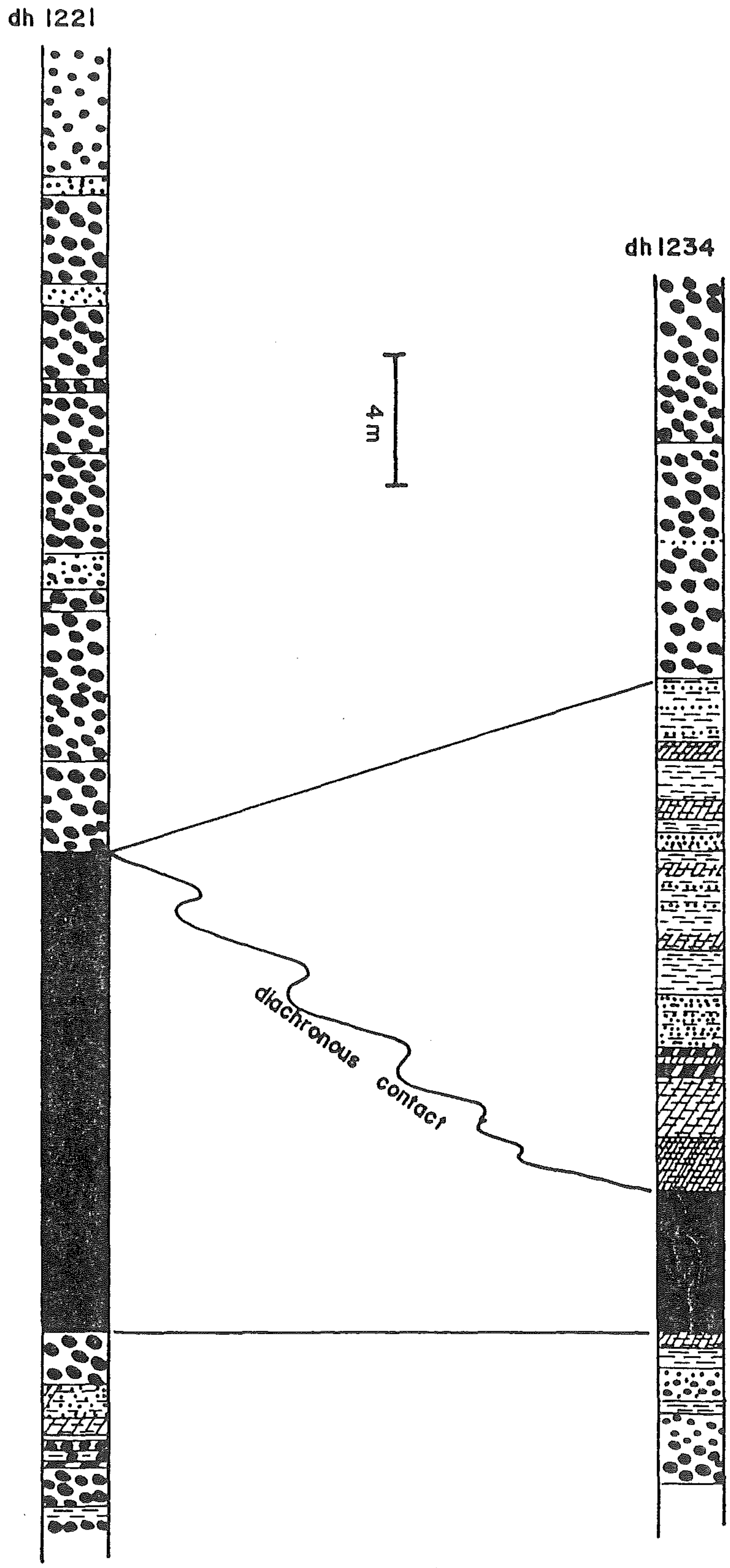


FIGURE 124. Stratigraphic relationships inferred for the Webb/Baynes area. Straight lines are time lines.

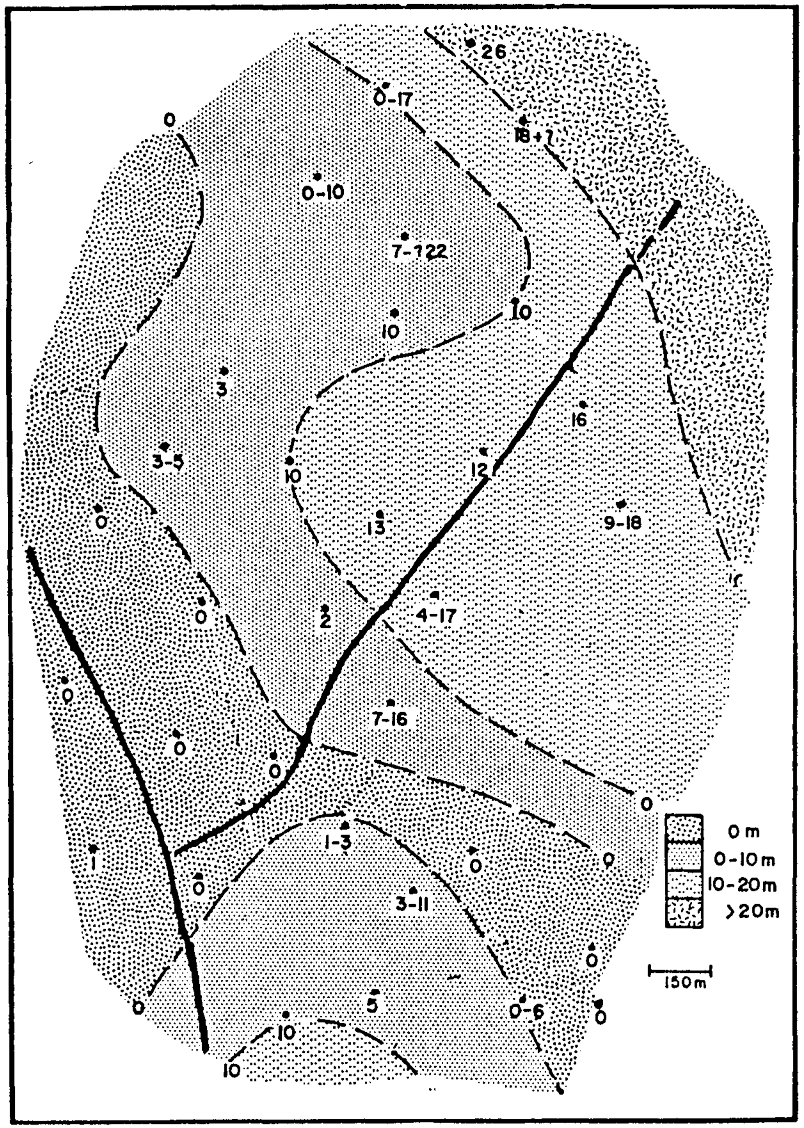


FIGURE 125. Isopach of muddy facies separating coal from the overlying coarse fluvial interval, Webb/Baynes Block.

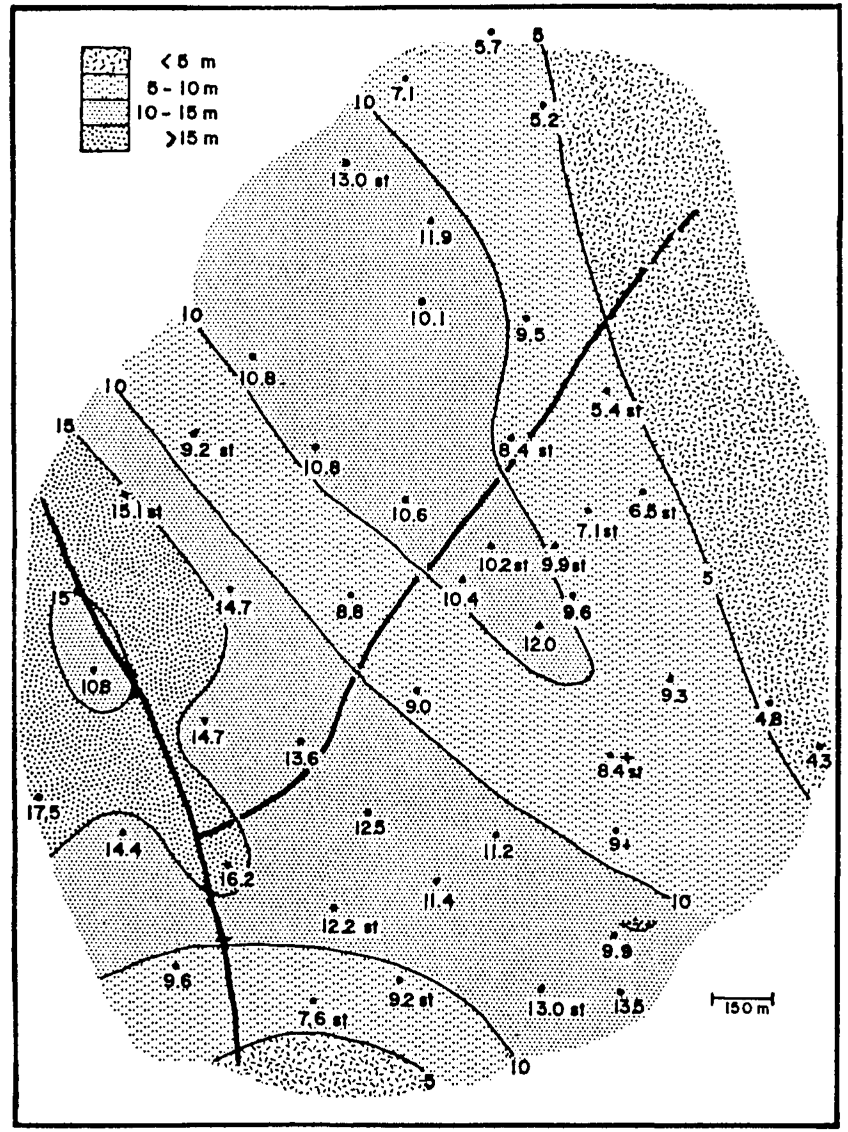


FIGURE 126. Isopach of Brunner seam thickness, Webb/Baynes Block.

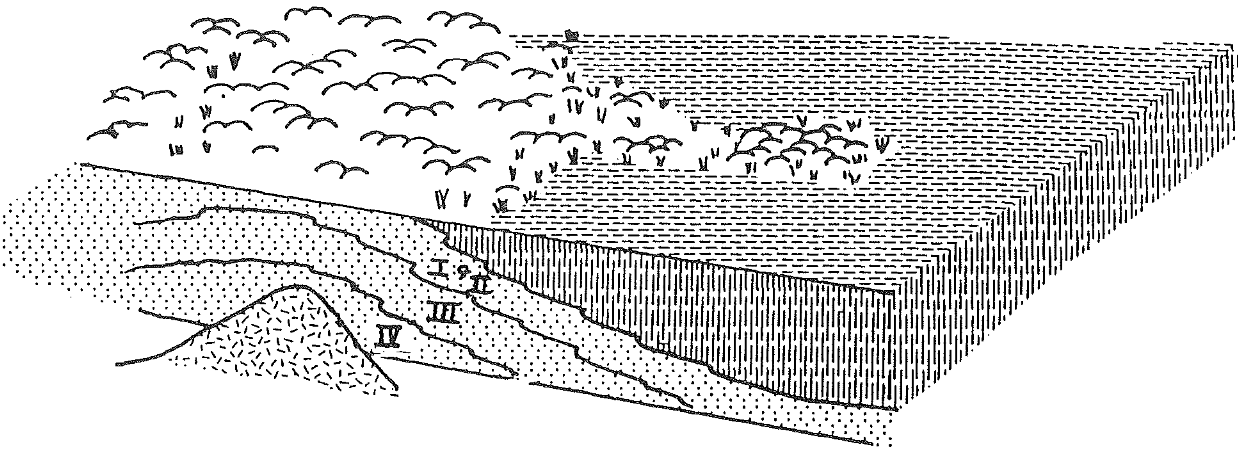


FIGURE 127a

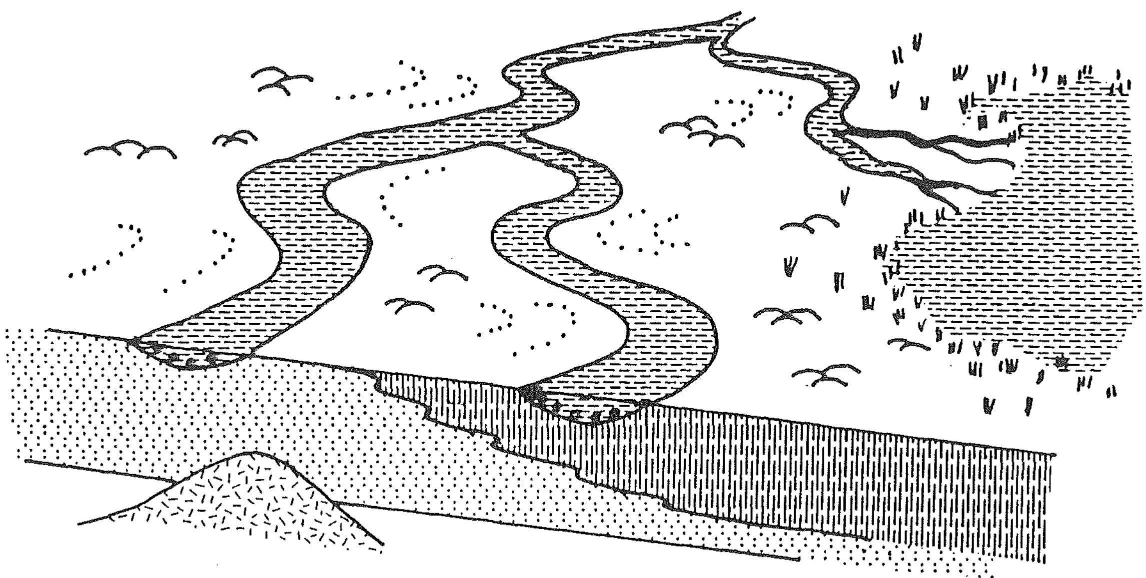


FIGURE 127b

FIGURE 127a. Paleoenvironmental reconstruction of Webb/Baynes study area during peat accumulation. Gradual drowning of swamp resulted in accumulation of muddy sediments in standing water to the east, contemporaneous with persistent peat accumulation in the west. Roman numerals refer to coal type zones. Small granite 'hill' protruding into seam crudely suggests a mechanism for local seam thinning as discussed in text.

FIGURE 127b. Termination of peat accumulation and muddy sedimentation by fluvial incursion into the Webb/Baynes study area.

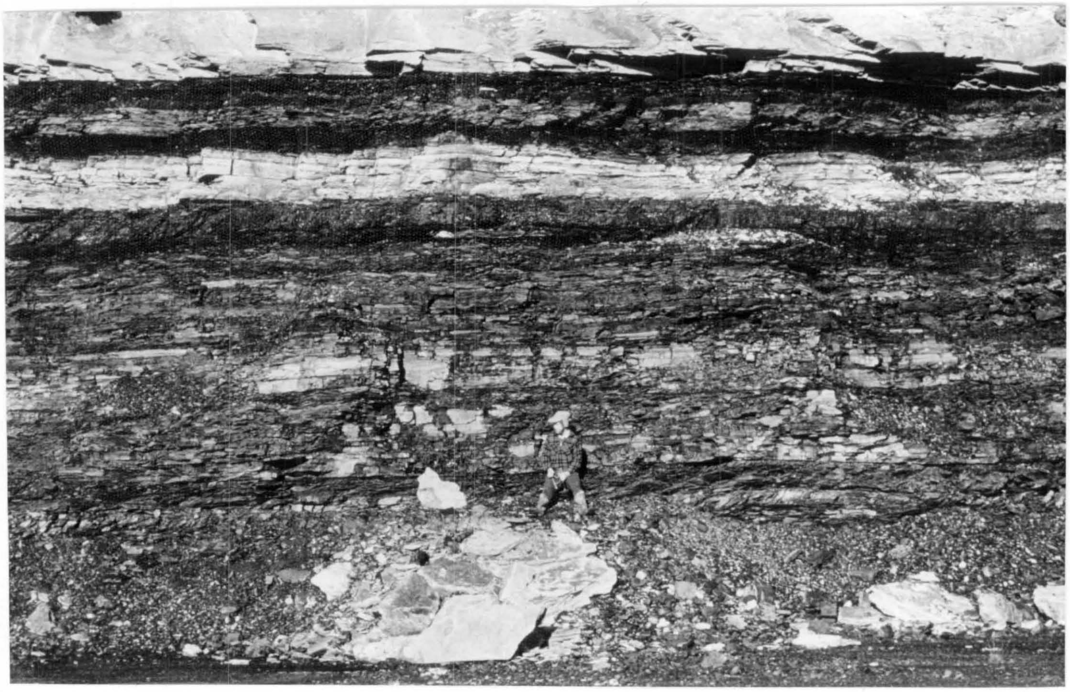


FIGURE 128. Fine carbonaceous mudstone facies substituting for coal southeast of the Webb/Baynes study area. Figure lower centre for scale.

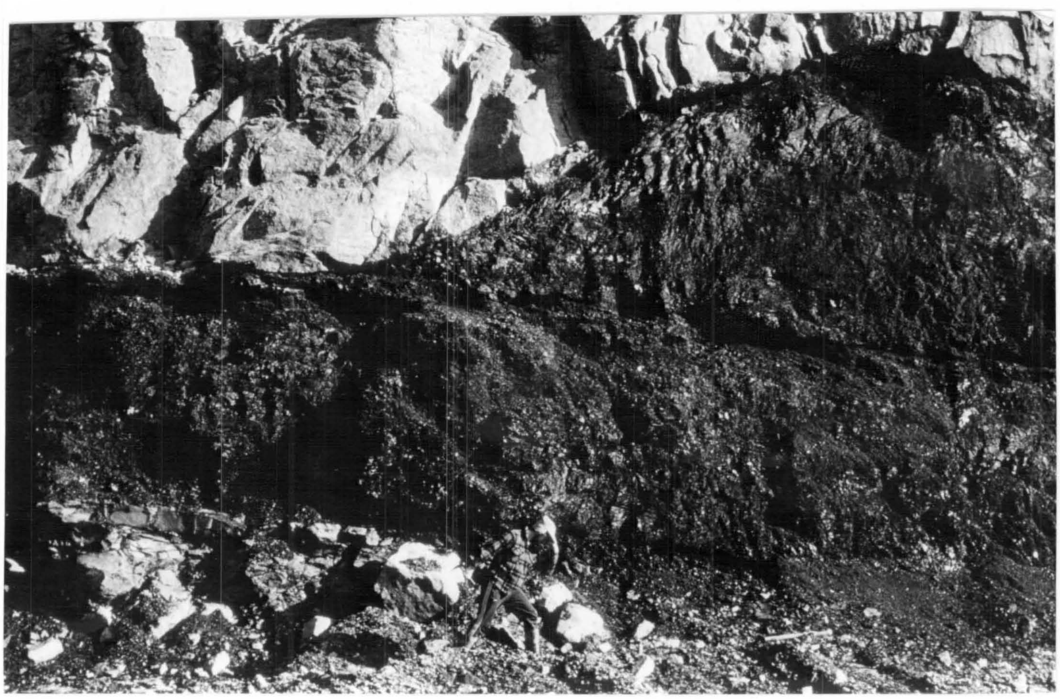


FIGURE 129. Sandstone channel eroding seam roof near bins at Webb Opencast. Figure lower centre for scale.

peat by fluvial channels (Fig. 129). However, anomalously thin seam intersections in Drillholes 1240 and 1241 (particularly the latter) appear more likely to result from the presence of a basement high; granite is close to the seam floor in both cases. The proximity of the Augustus Fault to these locations suggests that rates of subsidence may have been at least locally fault controlled, as postulated by Titheridge (in Newman, J. et al. 1980).

Beyond the study area, in the northeast and south, barren zones comprising carbonaceous mudstone take the place of the coal seam. These are interpreted to represent the end-member in the continuum high moor - low moor - bay/lagoon.

4.6.3 Paleoenvironmental significance of Webb/Baynes coal petrology and proximate analyses

(a) Introduction. Petrological work commenced before a full set of composite splits had been received from CRA. As far as permitted by the material available, samples for petrological appraisal were selected so that (1) the entire area of the programme was represented and (2) any vertical variability within seam profiles could be studied. Outcrop material was avoided because the seam was usually incompletely sampled due to poor exposure, and most samples were strongly weathered. Of the 45 remaining sample sites 20 were selected for study, involving a total of 58 composites, 25 of which were selected for reflectance measurement in addition to maceral investigations (Fig. 130).

(b) Results. Maceral analyses and reflectance measurements are presented with some pertinent elements of the CRA results in Table 8 and Figure 131. Maceral analysis values are expressed to ½% instead of the usual 1%, because many components occur in very small amounts. Two varieties of vitrinite defined specifically for the purposes of this and other Brunner coal studies are not part of the standard international nomenclature. The most important of these, 'indeterminate vitrinite', is described in Section 4.5.2, and a gradation from distinctly cellular telocollinite to indeterminate vitrinite in Webb/Baynes coals is illustrated in Figures 132 to 134. The other maceral, 'vitrinite intercalated with mineral matter' (Fig. 135) occurs in significant proportions only when mineral matter is abundant. The designation is used for material which cannot be differentiated into telocollinite and desmocollinite and would tend to

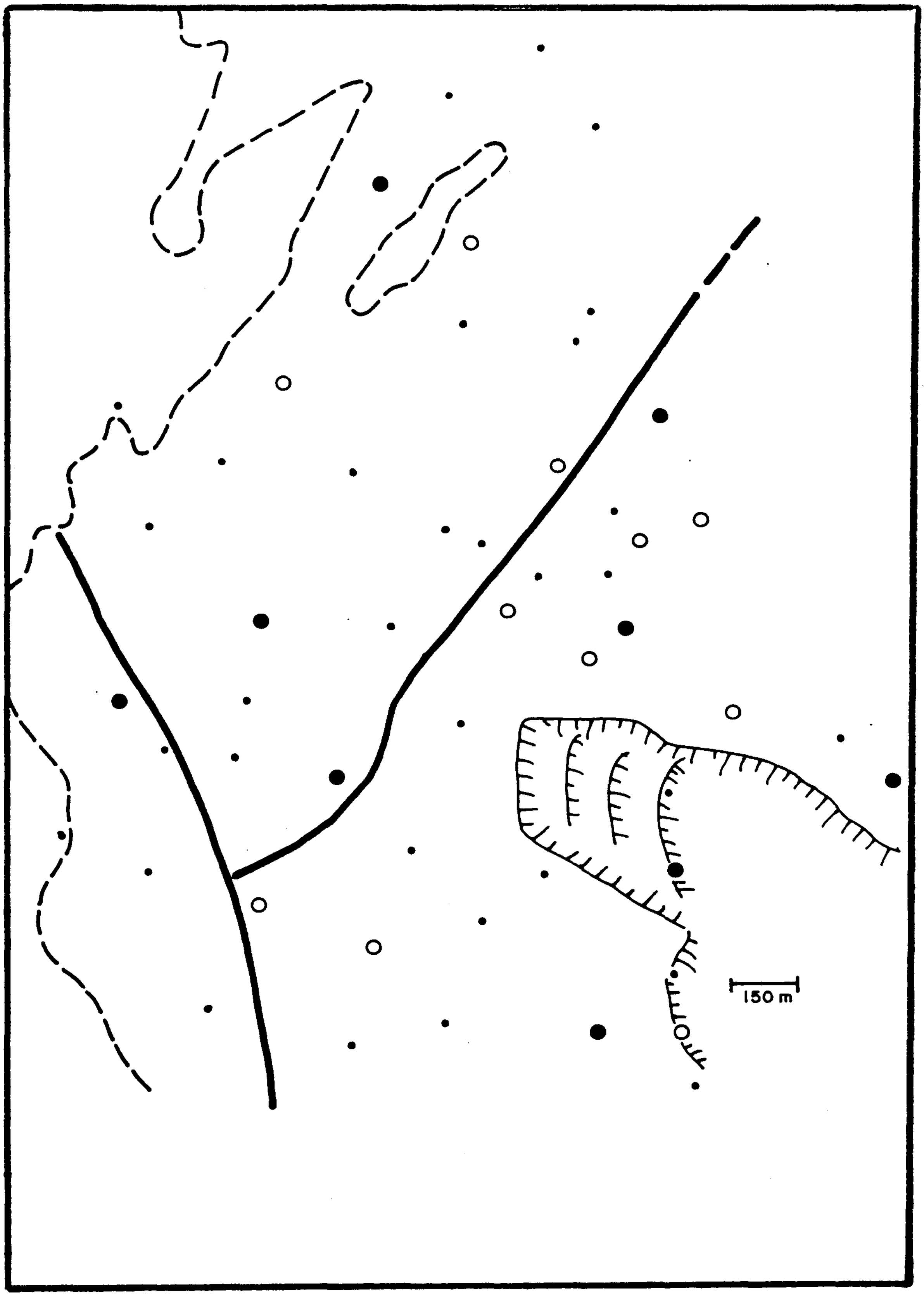


FIGURE 130. Webb/Baynes sample sites selected for petrological study. Small dots = sites not utilised, filled circles = sites from which composites were subject to maceral analysis and reflectance determination, open circles = sites from which composites were subject to maceral analysis only.

TABLE 8.

	Drillhole/Section No.		UG2	UG2	UG2	UG2	UG3	UG3	UG5	UG5	UG5	UG7	UG7	UG7	UG8	UG8
	Composite No.		1	2	3	4	1	2	1	2	3	1	2	3	1	2
	Coal Res. Ass. No.[2]		31/035	31/036	31/037	31/038	31/050	31/051	31/056	31/057	31/058	31/061	31/062	31/063	31/064	31/065
	Thickness (m)		1.80	3.60	2.40	0.90	3.00	0.60	1.8	1.2	3.0	3.6	4.8	1.2	9.6	1.8
proximate analyses	Moisture	- %	nd	nd	nd	nd	2.1	2.1	1.1	1.2	1.2	1.3	1.4	1.0	1.3	0.78
	Ash	- %	"	"	"	"	0.41	1.9	31.4	3.5	1.3	7.6	0.38	4.0	0.40	3.6
	Volatile matter	- %	"	"	"	"	35.1	34.7	26.0	34.0	32.7	33.1	33.7	33.1	33.9	33.7
	Fixed carbon	- %	"	"	"	"	62.4	61.3	41.5	61.3	64.8	58.0	64.5	61.9	64.4	61.9
	Calorific value MJ/Kg		"	"	"	"	34.25	33.66	23.29	34.63	35.06	32.16	34.88	33.32	35.10	33.84
	Calorific value Btu/lb		"	"	"	"	14,720	14,470	10,010	14,890	15,070	13,830	14,990	14,320	15,090	14,550
	Sulphur	- %	"	"	"	"	0.57	0.47	0.90	1.08	1.87	2.50	1.16	3.44	1.58	4.44
	Crucible Swelling No.		"	"	"	"	7	7	5	9	9+	9	9	9++	9++	9+++
	Volatile matter dmm½sf[1]	- %	"	"	"	"	35.9	35.9	34.2	35.2	33.1	35.2	34.1	33.9	34.2	34.2
Ultimate analyses	Carbon dasf	- %	"	"	"	"	84.8	84.7	83.1	87.0	87.4	86.6	86.5	87.1	86.8	88.1
	Hydrogen "	- %	"	"	"	"	5.5	5.5	6.0	5.6	5.5	5.7	5.5	5.6	5.5	5.6
	Nitrogen "	- %	"	"	"	"	1.4	1.3	1.2	1.3	1.2	1.3	1.2	1.0	1.3	1.0
	Oxygen "	- %	"	"	"	"	8.3	8.5	9.7	6.1	5.9	6.4	6.8	6.3	6.4	5.3
Maceral analyses	Desmocollinite	- %	79	71	71	62	67	73½	25½	85½	74	62	78	83½	80	77
	Telocollinite	- %	1	7½	10½	12	8½	8½	9	2½	11	8½	9	6	7½	3
	Vitrodetrinite	- %	9½	13	5½	½	17½	6½	tr	½	½	5½	6	1	4½	tr
	Indeterminate Vit.	- %	4½	4	6	13	1½	6½	9	4½	8½	4	3	4	2	14½
	Vitrinite intercalated with mineral matter	- %	-	-	-	3	-	-	23	-	-	7½	-	tr	-	-
	Liptodetrinite	- %	2½	2	1½	1	1½	2	1	2	2½	2	½	1½	1	½
	Resinite	- %	tr	½	tr)	½	tr	tr	tr) Σ½	½	tr	½	tr	tr	tr	tr
	Suberinite	- %	½	tr	tr)	tr	½	tr	tr)	tr	tr	tr	tr	tr	tr	tr
	Sporinite	- %	tr	tr	tr)	½	tr	½	tr	tr	tr	tr	½	tr	tr	tr
	Cutinite	- %	-	-	-	-	-	-	tr	-	-	tr	-	-	-	-
	Semifusinite	- %	2	1½	3½	½	2½	2	2	3	3	3½	3	1½	4	1½
	Sclerotinite	- %	½	tr	1	tr	½	tr	tr	tr	tr	tr	tr	tr	½	½
	Micrinite	- %	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	-	tr
	Clays, micas, quartz		tr	tr	tr	7	½	½	30	1	½	6	-	2½	½	2½
	Pyrite		½	½	tr	tr	tr	tr	tr	½	-	½	tr	tr	-	½
	Total vitrinite		94	95½	93	90½	94½	95	66½	93	94	87½	96	94½	94	94½
	Total exinite		3	2½	2½	2	2	2½	1½	2½	2½	2½	1	1½	1	½
	Total inertinite		2½	1½	4½	½	3	2	2	3	3	3½	3	1½	4½	2
	Total mineral matter		½	½	tr	7	½	½	30	1½	½	6½	tr	2½	½	3
	$\bar{R}o$ max	- %	-	-	-	-	0.89	0.90				0.93	0.96	0.94		
	Fluidity (max. ddm)		45,174	364	162	17,401	18	12	620	3,600	331	2,040	154	664	638	25,145
	"Type Number"		-	-	-	-	II	II	II	II	II/III	II	II	II	II	II

TABLE 8. Analytical information for Brunner coal samples from the Webb/Baynes area.

Notes: 1. Volatile matter corrected for the contribution made by mineral matter and sulphur. The correction method is presented in Appendix 8.

2. (UC Sample No. equivalents appear in Appendix 5.)

TABLE 8 cont.

		F2	F2	F3	F3	DH 1215	DH 1215	DH 1215	DH 1215	DH 1215	DH 1215	DH 1216	DH 1216	DH 1218	DH 1218
	Drillhole/Section No.	F2	F2	F3	F3	DH 1215	DH 1215	DH 1215	DH 1215	DH 1215	DH 1215	DH 1216	DH 1216	DH 1218	DH 1218
	Composite No.	1	2	1	2	1	2	3	4	5	6	1	2	1	2
	Coal Res. Ass. No.[2]	31/059	31/069	31/086	31/087	31/044	31/045	31/046	31/047	31/048	31/049	31/040	31/041	31/113	31/114
	Thickness (m)	5.4	7.6	8.0	1.0	2.48	0.76	1.14	0.93	2.73	2.30	5.24	5.00	8.83	4.26
proximate analyses	Moisture	2.7	2.0	1.4	1.0	0.91	1.0	0.96	0.98	1.3	1.0	0.83	0.91	1.4	1.2
	Ash	1.2	0.48	0.28	1.4	0.88	11.1	11.4	3.7	1.1	18.6	4.0	0.54	6.5	2.6
	Volatile matter	32.4	32.4	34.3	34.3	38.4	33.9	33.8	33.2	32.9	30.0	32.9	31.7	30.0	28.9
	Fixed carbon	63.7	65.1	64.0	63.3	59.8	54.0	53.8	62.1	64.7	50.4	62.3	66.9	62.1	67.3
	Calorific value MJ/Kg	32.98	33.93	35.13	34.7	34.95	31.57	31.45	34.6	34.84	27.57	34.52	35.42	33.0	34.68
	Calorific value Btu/lb	14,180	14,590	15,100	14,920	15,030	13,570	13,520	14,870	14,980	11,850	14,840	15,230	14,190	14,910
	Sulphur	1.92	2.52	1.54	3.08	4.15	2.01	2.10	1.59	2.60	3.48	1.04	2.53	1.06	2.94
	Crucible Swelling No.	1	4	9	9+	9++	8½	9	9+	9+	9	9+	8½	9	9
	Volatile matter dmm½sf[1]	33.2	32.8	34.6	34.5	38.6	37.2	37.1	34.2	33.1	34.6	34.0	31.7	31.7	29.2
Ultimate analyses	Carbon dasf	84.8	87.0	86.7	87.5	87.1	86.9	86.7	87.5	87.3	84.9	87.6	88.1	87.8	89.1
	Hydrogen "	5.2	5.2	5.5	5.5	5.7	6.0	5.9	5.7	5.4	5.8	5.6	5.4	5.4	5.3
	Nitrogen "	1.2	1.2	1.3	1.2	1.1	1.2	1.1	1.2	1.1	0.9	1.2	1.1	1.3	1.2
	Oxygen "	8.8	6.7	6.5	5.8	6.1	5.9	6.3	5.6	6.2	8.4	5.6	5.4	5.5	4.4
Maceral analyses	Desmocollinite	76	76	76	81	68½	62	63	68½	83	62	64½	82	75½	60
	Telocollinite	7	7½	6	10	8	11½	7	20	7	13½	18½	7	1	½
	Vitrodetrinite	4½	5	8	1½	7	½	tr	tr	2	1	1½	2	½	½
	Indeterminate Vit.	4½	3	2	1	8½	9½	13	6	2½	5	5½	1	16	33
	Vitrinite intercalated with mineral matter	tr	-	-	-	-	3	2½	½	-	5	2	-	-	-
	Liptodetrinite	2	2	1½	1	3½	3	½	tr	1	½	1½	1	½	tr) Σ½
	Resinite	½	1	tr) Σ1	tr	tr	tr	1½	1	1	tr	1	1	tr	tr)
	Suberinite	tr	tr	½)	tr	tr	tr	1	½	½	½	tr	tr	tr	-
	Sporinite	tr	tr	tr	tr	tr	tr	½	½	1	tr	tr	tr	tr	-
	Cutinite	tr	tr	tr	-	tr	-	-	-	-	-	-	-	-	-
	Semifusinite	5	5	4½	4½	3	2	1½	1½	1½	1	2½	5	1	2
	Sclerotinite	tr	tr	2	½	tr	tr	tr	tr	tr	tr	tr	½	½	1
	Micrinite	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
	Clays, micas, quartz	½	½	tr	½	tr	8½	9½	1½	½	11½	3	½	5	2½
	Pyrite	tr	-	tr	tr	½	tr	tr	tr	tr	tr	tr	tr	tr	tr
	Total vitrinite	92	91½	92	93½	93	86½	85½	95	94½	86½	92	92	93	94
	Total exinite	2½	3	2½	1	3½	3	3½	2	3½	1	2½	2	½	½
	Total inertinite	5	5	5½	5	3	2	1½	1½	1½	1	2½	5½	1½	3
	Total mineral matter	½	½	tr	½	½	8½	9½	1½	½	11½	3	½	5	2½
	$\bar{R}o$ max			0.95	0.93	0.82	0.89	0.88	0.96	0.98	0.93				
	Fluidity (max. ddm)	2	3	899	33,240	49,454	38,044	39,251	27,284	696	1,728	24,278	1,502		
	"Type Number"	II/III	II/III	II	II	I	I	I	II	III	II	II	III	II	III

TABLE 8 cont.

	Drillhole/Section No.	DH 1220	DH 1220	DH 1222	DH 1222	DH 1222	DH 1226	DH 1226	DH 1226	DH 1226	DH 1226	DH 1226	DH 1226	DH 1226
	Composite No.	1	2	1	2	3	1	2	3	4	5	6	7	8
	Coal Res. Ass. No.[2]	31/069	31/070	31/083	31/084	31/085	31/075	31/076	31/077	31/078	31/079	31/080	31/081	31/082
	Thickness (m)	11.73	1.30	3.70	7.30	2.51	0.78	2.27	1.83	1.63	1.74	0.60	0.70	0.60
proximate analyses	Moisture	1.2	0.8	1.0	1.1	0.8	1.2	0.9	1.1	1.2	1.7	1.2	2.3	1.0
	Ash	0.21	2.4	4.6	0.28	4.8	4.0	0.13	0.51	0.26	0.12	0.32	1.2	3.8
	Volatile matter	32.0	31.7	31.5	29.5	27.7	29.8	30.6	29.4	28.5	26.7	27.9	26.9	28.4
	Fixed carbon	66.6	65.1	62.9	69.1	66.7	65.0	68.4	69.0	70.0	71.5	70.6	69.6	66.8
	Calorific value MJ/Kg	35.87	34.22	34.11	35.88	33.72	34.15	35.62	35.42	35.68	34.73	35.01	33.37	33.82
	Calorific value Btu/lb	15,420	14,710	14,660	15,420	14,500	14,680	15,310	15,230	15,340	14,930	15,050	14,350	14,540
	Sulphur	1.40	4.21	2.81	1.14	3.78	1.02	0.72	0.67	0.90	1.62	3.03	3.41	3.84
	Crucible Swelling No.	9+	9++	9	9	9	9+	9+	9+	9	3½	8	½	9
	Volatile matter dmm½sf[1]	32.2	31.8	32.4	29.6	28.0	30.9	30.8	29.7	28.7	26.8	27.6	26.9	28.6
Ultimate analyses	Carbon dasf	87.8	88.8	88.3	88.4	88.8	87.9	88.3	88.0	88.5	87.5	88.4	86.9	88.5
	Hydrogen "	5.4	5.4	5.6	5.3	5.3	5.5	5.3	5.3	5.2	5.1	5.1	4.9	5.3
	Nitrogen "	1.3	1.1	1.2	1.2	1.0	1.2	1.2	1.2	1.3	1.2	1.1	1.0	1.0
	Oxygen "	5.5	4.7	4.9	5.1	4.9	5.4	5.2	5.5	5.0	6.2	5.4	7.2	5.2
Maceral analyses	Desmocollinite	84	80	76	78	61½	78	84	86	88	86	90	84½	68½
	Telocollinite	4	1½	13	4	½	½	1	2	4½	3	1	1	1
	Vitrodetrinite	½	½	1½	1	½	-	tr	tr	tr	tr	tr	tr	tr
	Indeterminate Vit.	7	9½	1	10½	30½	14½	12½	10	2	6½	2½	10	26½
	Vitrinite intercalated with mineral matter	-	-	½	-	-	1½	-	-	-	-	-	-	-
	Liptodetrinite	1	½	1½	½	1	tr	½	½	1	tr	1	½	tr
	Resinite	tr	½	1	tr	tr	tr	1	tr	tr	tr	tr	½	½
	Suberinite	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
	Sporinite	tr	-	½	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
	Cutinite	-	-	-	-	-	-	-	-	-	-	-	tr	-
	Semifusinite	3½	5	3	5½	2	3	½	1½	4	4	5	3½	1½
	Sclerotinite	tr	½	½	½	1	tr	½	tr	½	½	tr	tr	tr
	Micrinite	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
	Clays, micas, quartz	tr	2	1½	tr	3	2½	-	tr	-	tr	½	tr	2
	Pyrite	-	tr	tr	-	tr	tr	-	-	-	tr	tr	tr	tr
	Total vitrinite	95½	91½	92	93½	93	94½	97½	98	94½	95½	93½	95½	96
	Total exinite	1	1	3	½	1	tr	1½	½	1	tr	1	1	½
	Total inertinite	3½	5½	3½	6	3	3	1	1½	4½	4½	5	3½	1½
	Total mineral matter	tr	2	1½	tr	3	2½	-	-	-	tr	½	tr	2
	$\bar{R}o$ max	1.04	1.08	1.02	1.10	1.17								
	Fluidity (max. ddm)	954	11,166	7,972	576	1,427	834	412	206	64	1	19	0	322
	"Type Number"	II	II	II	III	IV	II/III	II/III	III	III	IV	III/IV	IV	III

TABLE 8 cont.

Drillhole/Section No.	DH 1227	DH 1227	DH 1227	DH 1228	DH 1228	DH 1228	DH 1228	DH 1232	DH 1232	DH 1234	DH 1235	DH 1236	DH 1236	DH 1236
Composite No.	1	2	3	1	2	3	4	1	2	1	1	1	2	3
Coal Res. Ass. No.[2]	31/088	31/089	31/090	31/071	31/072	31/073	31/074	30/106	30/107	31/095	31/109	31/103	31/104	31/105
Thickness (m)	1.99	1.76	9.41	3.03	1.07	5.16	2.14	5.40	1.2	4.2	1.18	1.2	3.9	2.4
proximate analyses: Moisture	1.1	1.3	1.1	1.0	1.1	1.0	0.8	1.2	0.72	0.94	1.1	1.1	1.3	1.1
Ash	33.5	1.6	0.86	36.3	2.0	0.50	1.8	2.6	13.5	4.7	2.8	2.1	0.37	1.5
Volatile matter	24.2	30.2	28.8	24.1	31.4	30.4	30.9	32.0	30.6	33.8	34.0	34.5	32.9	32.6
Fixed carbon	41.2	66.9	69.2	38.6	65.5	68.1	66.5	64.2	55.2	60.6	62.1	62.3	65.4	64.8
Calorific value MJ/kg	22.70	35.17	35.27	21.44	34.78	35.61	34.36	34.64	30.14	33.71	34.51	34.64	35.25	34.82
Calorific value btu/lb	9,760	15,120	15,160	9,220	14,950	15,310	14,770	14,890	12,960	14,490	14,840	14,890	15,150	14,970
Sulphur	0.51	0.74	2.02	0.57	0.73	1.46	4.55	1.68	3.45	3.10	2.4	2.97	1.39	2.47
Crucible Swelling No.	5½	8½	8½	3½	9	9+	9+	9	9	9+	9	9+	9	9
Volatile matter dmm½sf[1]	32.2	30.8	28.9	33.0	32.0	30.5	30.7	32.7	33.6	34.9	34.8	35.0	33.2	33.0
Ultimate analyses: Carbon dasf	83.3	87.8	88.4	83.4	87.6	87.8	88.8	87.4	87.0	87.7	87.4	87.5	87.2	87.7
Hydrogen "	6.0	5.4	5.2	6.2	5.5	5.3	5.4	5.5	5.7	5.7	5.6	5.6	5.4	5.4
Nitrogen "	1.2	1.2	1.1	1.1	1.2	1.2	1.0	1.3	1.0	1.2	1.2	1.1	1.2	1.1
Oxygen "	9.5	5.6	5.3	9.3	5.7	5.7	4.8	5.8	6.3	5.4	5.8	5.8	6.2	5.8
Maceral analyses: Desmocollinite	30	82	73½	27	88	84	84½	88	72	74	82	85½	80	80½
Telocollinite	3	2	tr	4½	1½	4½	½	½	2½	7	4½	3	6½	6½
Vitrodetrinite	tr	3	½	½	tr	2½	tr	tr	½	tr	tr	½	½	2
Indeterminate Vit.	10	8	23	15½	7	5½	7	6½	7	7	7	5	4	3½
Vitrinite intercalated with mineral matter	17	-	-	21½	-	-	-	-	5½	1	-	-	-	-
Liptodetrinite	tr)	1	1	tr	½	½	½	1	½	2½	1½	1½	2	3
Resinite	tr) Σ1	1	tr	½	tr)	½	1	1	tr	1	1	½	tr	tr
Suberinite	tr)	tr	tr	tr	tr) Σ½	tr	tr	tr	tr	tr	tr	½	tr	½
Sporinite	tr)	tr	tr	tr	tr)	tr	tr	tr	tr	tr	tr	tr	½	tr
Cutinite	-	-	-	tr	tr)	-	-	tr	-	-	-	tr	tr	tr
Semifusinite	1	2	½	3	1½	2	4½	2½	1	4	2½	2	5	3½
Sclerotinite	tr	tr	1½	tr	tr	tr	½	tr	tr	tr	tr	tr	½	tr
Micrinite	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
Clays, micas, quartz	37	1	tr	27½	1	½	tr	½	9½	3½	1½	1	1	½
Pyrite	tr	tr	tr	tr	tr	tr	1½	tr	1½	tr	tr	½	tr	tr
Total vitrinite	61	95	97	69	96½	96½	92	95	87½	89	93½	94	91	92½
Total exinite	1	2	1	½	1	1	1½	2	½	3½	2½	2½	2½	3½
Total inertinite	1	2	2	3	1½	2	5	2½	1	4	2½	2	5½	3½
Total mineral matter	37	1	tr	27½	1	½	1½	½	11	3½	1½	1½	1	½
$\bar{R}o$ max	0.97	1.07	1.10							0.96				
Fluidity (max. ddm)	757	370	250	875	430	331	2,416			31,074	36,077			
"Type Number"	II	II	III	I/II	II	II/III	II/III	III	II/III	II	II	II	II/III	II/III

TABLE 8 cont.

		DH 1241	DH 1241	DH 1241
	Drillhole/Section No.	DH 1241	DH 1241	DH 1241
	Composite No.	1	2	3
	Coal Res. Ass. No.[2]	31/110	31/111	31/112
	Thickness (m)	2.35	5.0	2.85
proximate analyses	Moisture	2.6	1.1	0.86
	Ash	1.6	0.36	2.8
	Volatile matter	32.4	30.3	27.2
	Fixed carbon	63.4	68.2	69.1
	Calorific value MJ/Kg	33.08	36.08	34.33
	Calorific value btu/lb	14,220	15,510	14,760
	Sulphur	3.55	1.14	3.83
	Crucible Swelling No.	8½	9	9+
	Volatile matter dmm½sf[1]	33.2	30.5	27.1
Ultimate analyses	Carbon dasf	86.7	88.6	89.8
	Hydrogen "	5.3	5.3	5.1
	Nitrogen "	1.1	1.3	1.1
	Oxygen "	6.9	4.8	4.0
Maceral analyses	Desmocollinite	89½	52½	28½
	Telocollinite	3½	2½	½
	Vitrodetrinite	-	1	-
	Indeterminate Vit.	4	40	67
	Vitrinite intercalated with mineral matter	-	-	-
	Liptodetrinite	½	1	½
	Resinite	tr	tr	tr
	Suberinite	½	tr	tr
	Sporinite	tr	tr	tr
	Cutinite	-	-	-
	Semifusinite	1	2	½
	Sclerotinite	-	tr	tr
	Micrinite	tr	tr	tr
	Clays, micas, quartz	tr	-	2
	Pyrite	1	tr	1
	Total vitrinite	97	97	96
	Total exinite	1	1	½
	Total inertinite	1	2	½
	Total mineral matter	1	tr	3
	$\bar{R}o$ max	0.94	1.08	1.19
	Fluidity (max. ddm)	71	912	952
	"Type Number"	I	III	IV

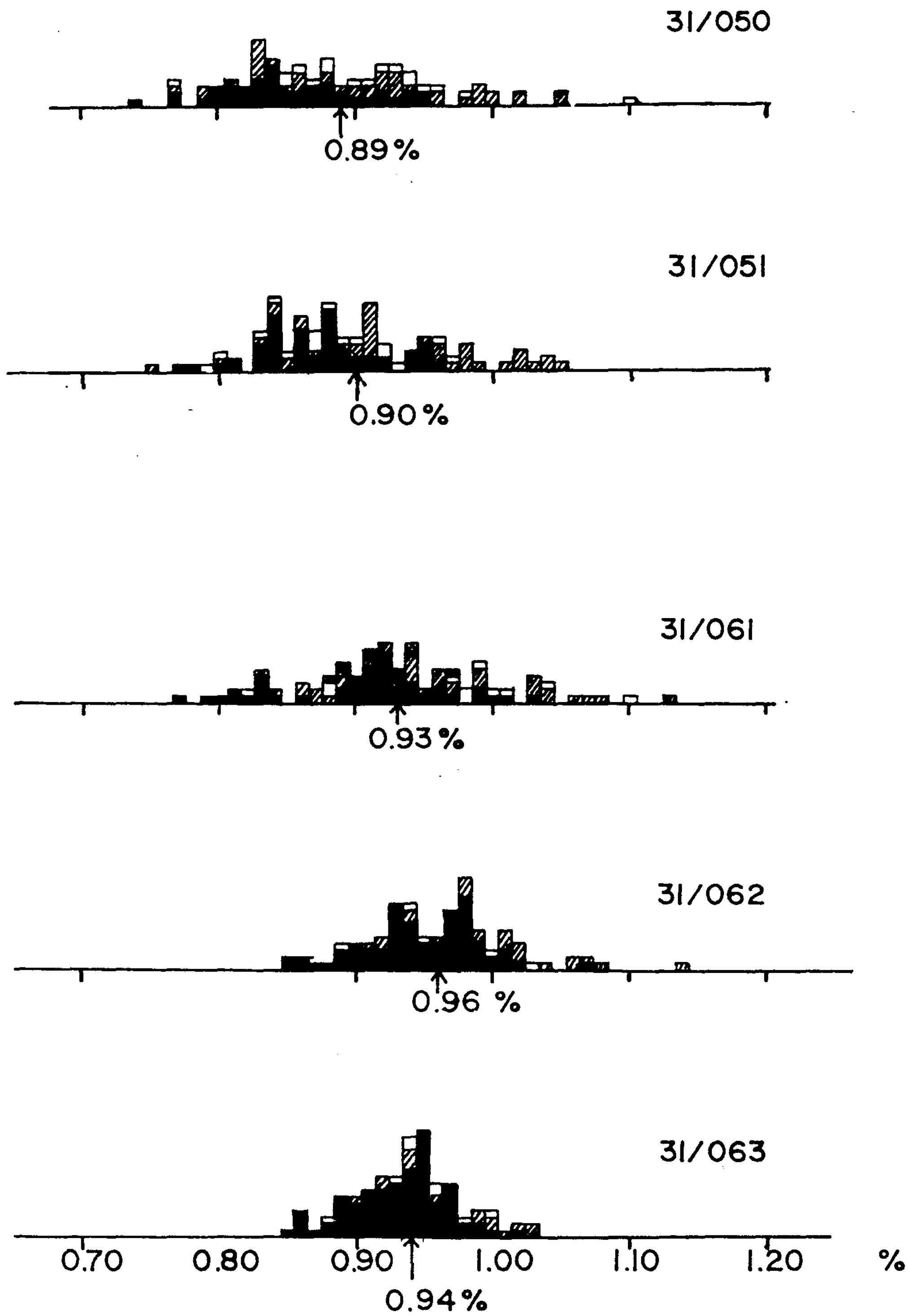


FIGURE 131. Reflectograms for selected Webb/Baynes samples, showing average vitrinite reflectance ($\bar{R}o$ max) in each case.

solid black = desmocollinite
hatched = telocollinite
cross hatched = vitrinite intercalated with mineral matter
unshaded = indeterminate vitrinite
▬ = one measurement

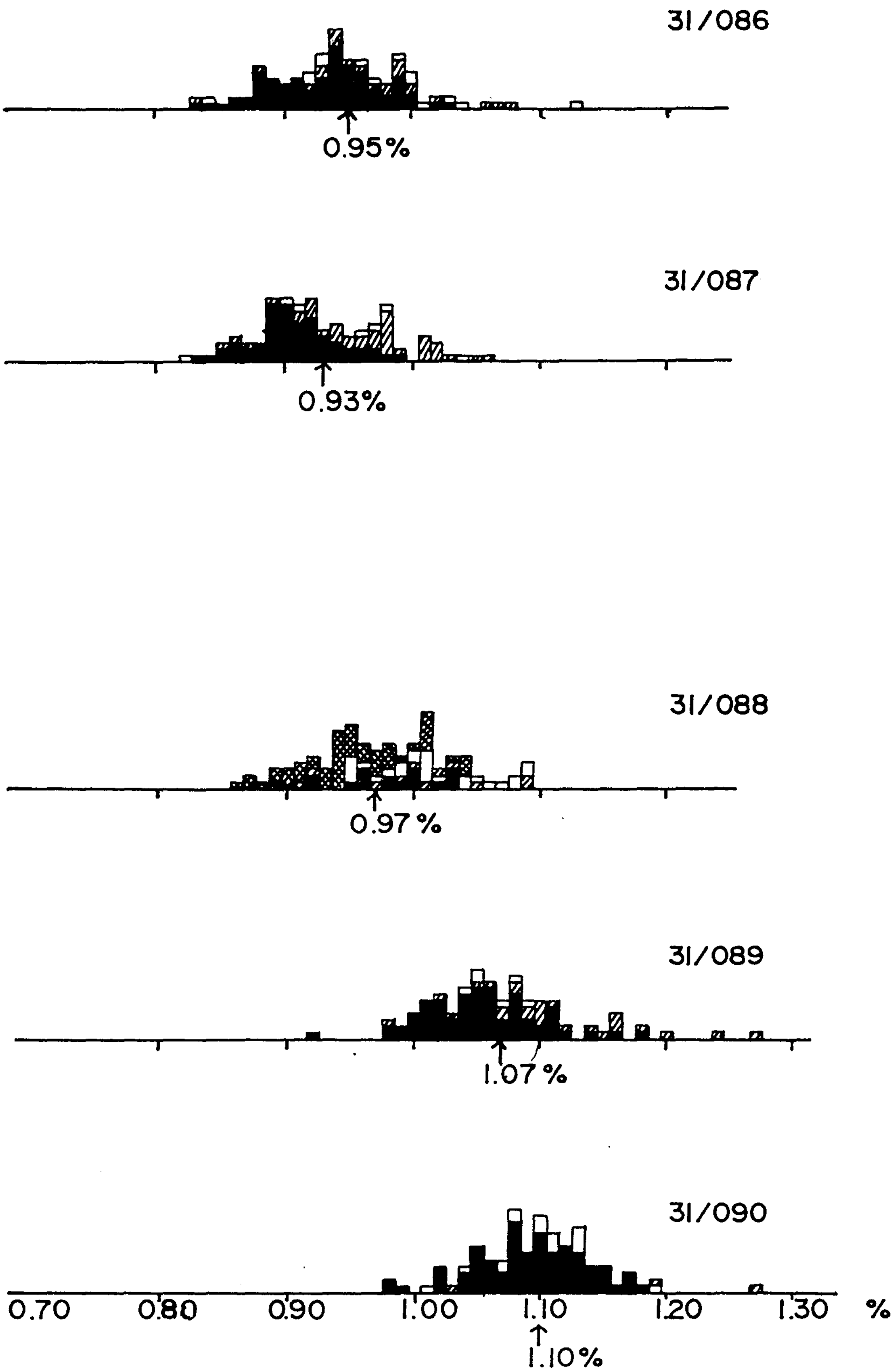


FIGURE 131 Continued.

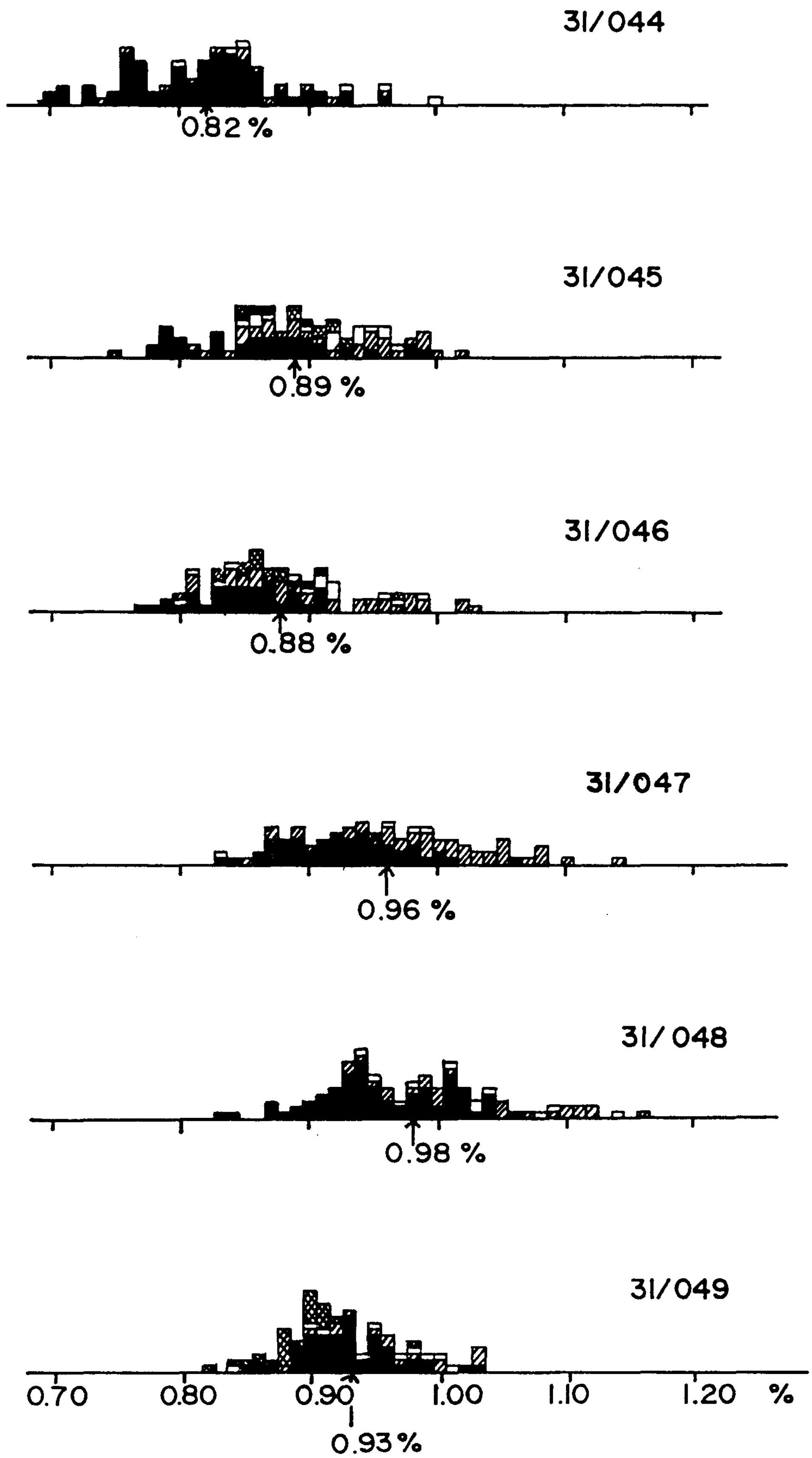


FIGURE 131 Continued.

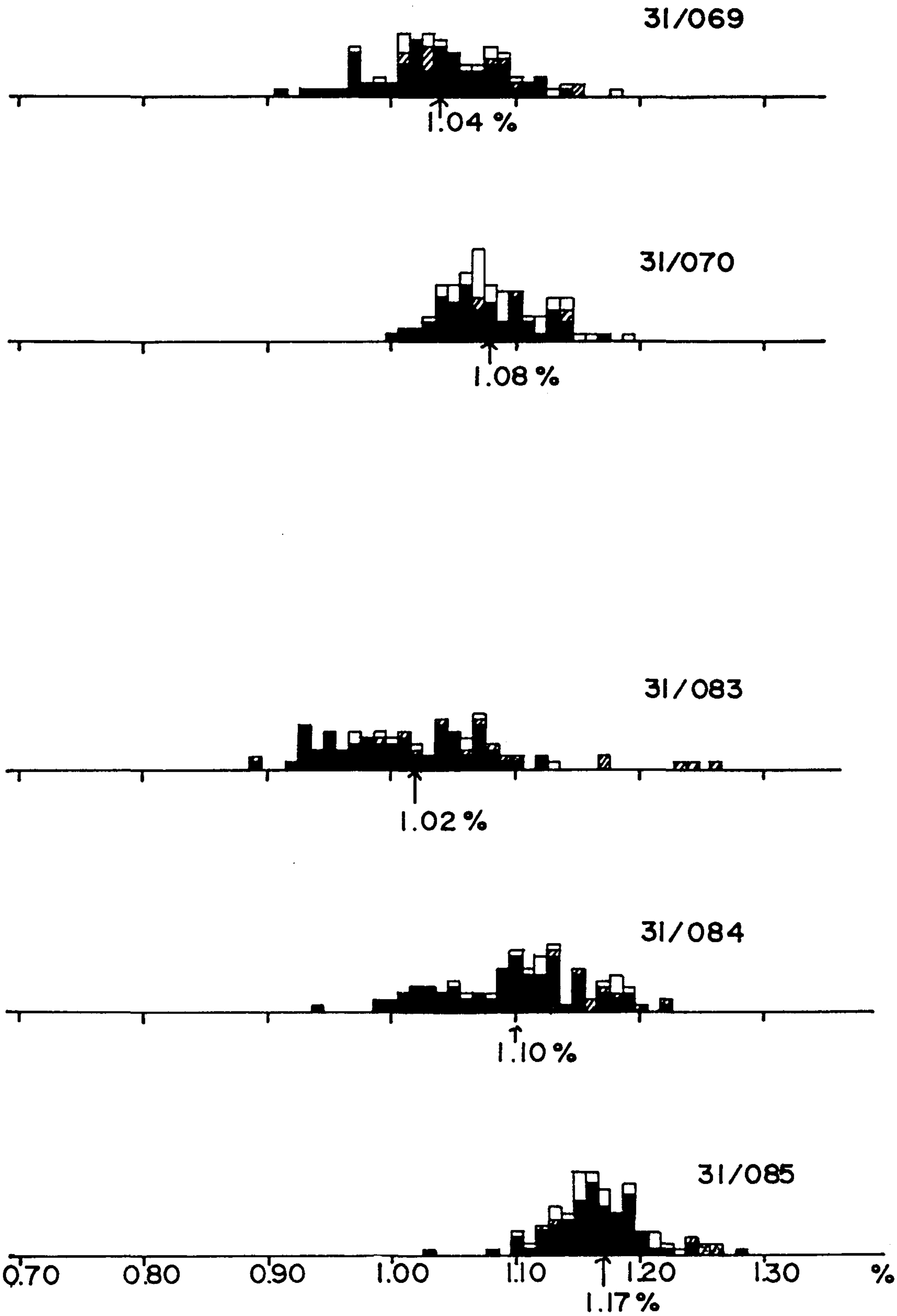


FIGURE 131 Continued.

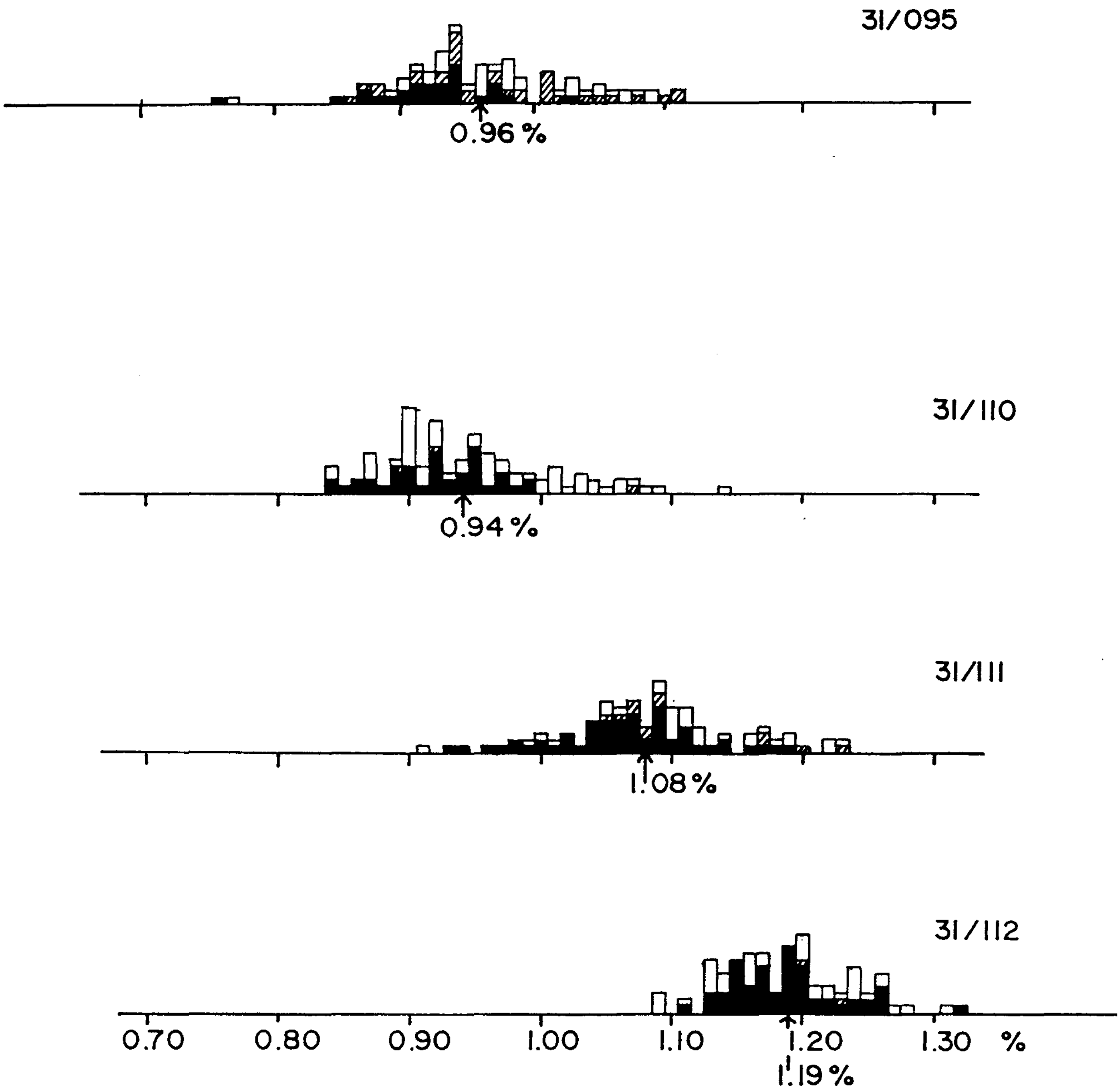


FIGURE 131 Continued.

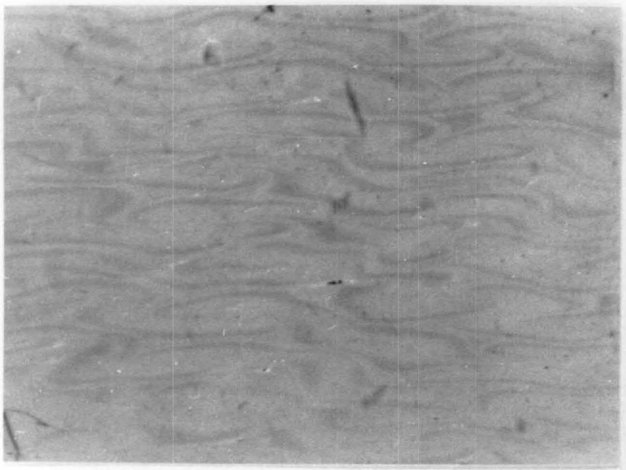


FIGURE 132.

Distinctly cellular telocollinite. Sample 31/063, UG7, horizontal field 0.25mm.

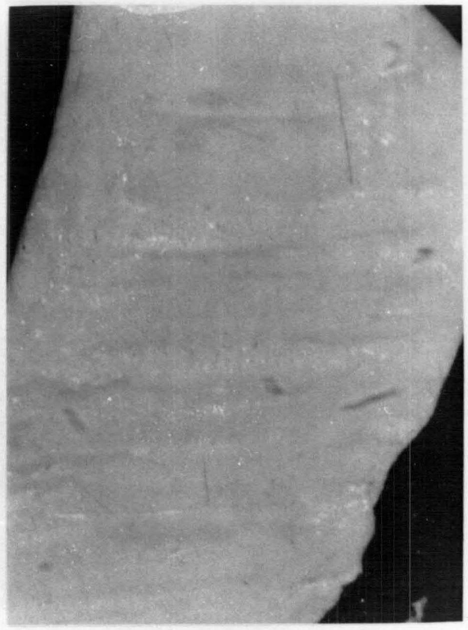


FIGURE 133.

Indistinctly cellular telocollinite. Sample 31/085, drillhole 1222, horizontal field 0.15mm.

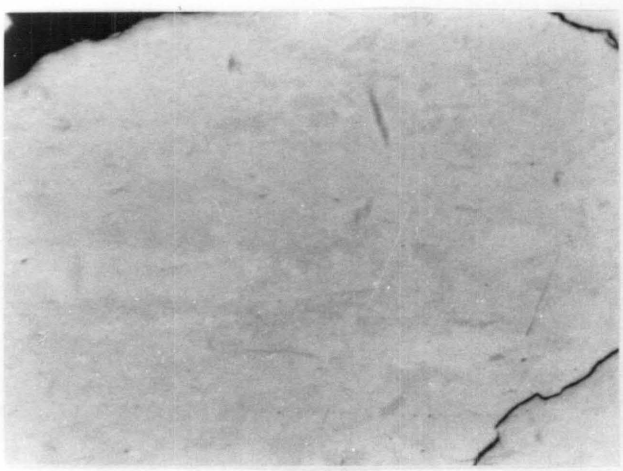


FIGURE 134.

Uniform (featureless) desmocollinite. Sample 31/112, drillhole 1241, horizontal field 0.25mm.

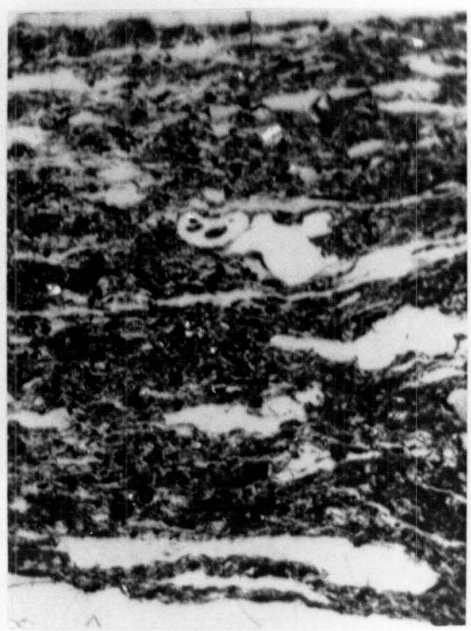


FIGURE 135.

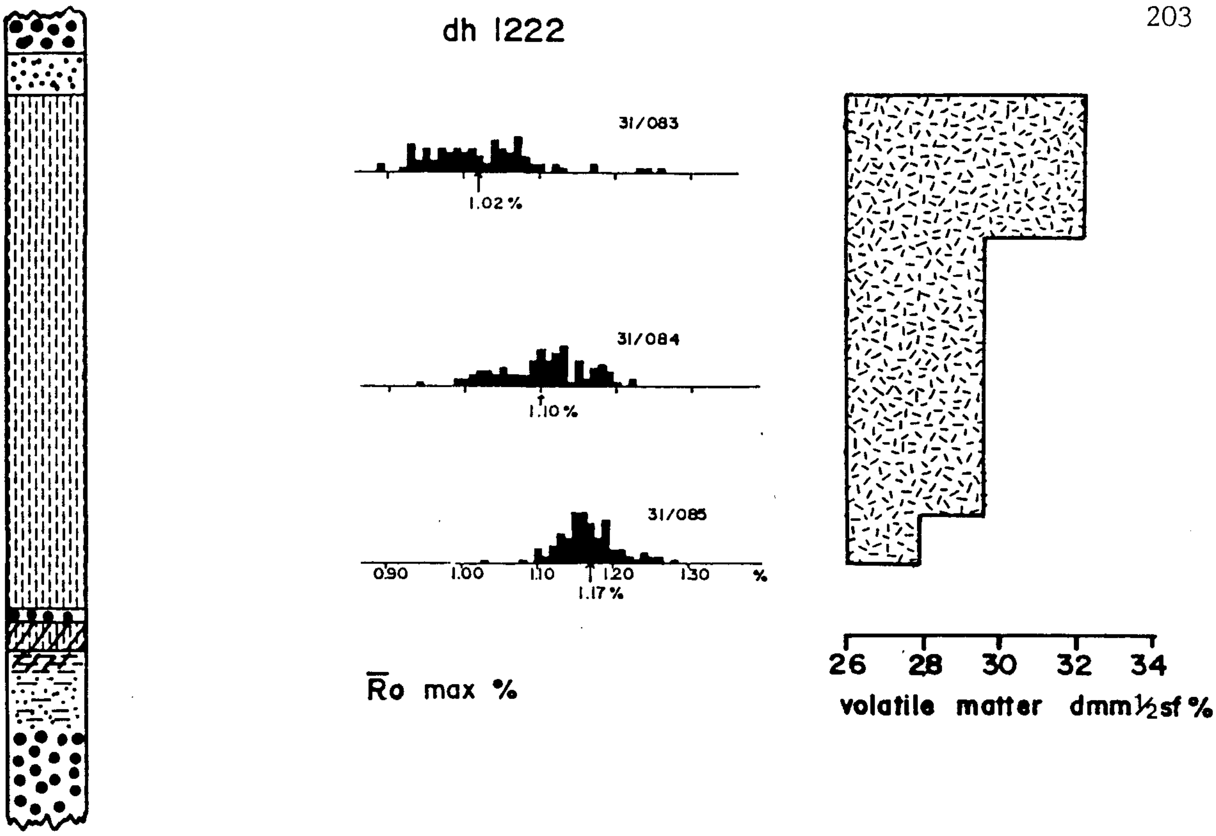
Vitrinite intercalated with mineral matter. Sample 31/088, drillhole 1227, horizontal field 0.15mm.

be lumped together with desmocollinite in a conventional analysis. Fusinite is omitted from Table 8 because it is absent from the coal.

Histograms of reflectance measurements (Fig. 131) graphically distinguish 4 vitrinite types. The distribution of values demonstrates that reflectance variability between samples is not a consequence of changes in the proportions of different vitrinite types.

(c) Discussion. The petrological results, coupled with volatile matter yields (Table 8), provide corroborative evidence in support of the general paleoenvironmental interpretation in Section 4.6.2. The writer's work on other West Coast coals has shown that oxygen availability, as controlled by water table level, is one of the most important influences on peat character and hence coal properties in both the Paparoa and Brunner Coal Measures. In general, volatile matter and vitrinite reflectance are chiefly affected; given equal rank volatile matter tends to be relatively high, and reflectance relatively low, in coals which accumulated in a waterlogged environment. Where reflectance varies significantly within serial samples of a Webb/Baynes seam profile the trend is almost invariably for values to decline upwards (Table 8, Fig. 136) which is consistent with a gradual rise in water level within the swamp as proposed in 4.6.2(b). As discussed previously, in cases where vitrinite is a very major component as it is in the Webb/Baynes coals, variations in volatile matter content between coals of equal rank can be attributed to differences in *vitrinite* composition as opposed to variations in the abundance or composition of exinite and inertinite. The existence of a consistent inverse relationship between volatile matter and vitrinite reflectance in suites of such coals (Fig. 137) also indicates that vitrinite composition is an important variable.

The degree to which lateral variations in volatile matter and reflectance are due to lateral type variations is difficult to establish. Reflectance tends to be highest and volatile matter lowest where the seam is thickest (Figs 138 & 139), i.e., where peat accumulation is postulated to have occurred on relatively high ground, hence in relatively well drained, well oxygenated swamps (4.6.2(b)). However, regional rank trends (Suggate 1959) indicate that an increase in rank equivalent to approximately one "Suggate rank number" can be expected between eastern (Suggate rank 13) and western (Suggate rank 14) samples in the study area, entailing a westward decline in volatile



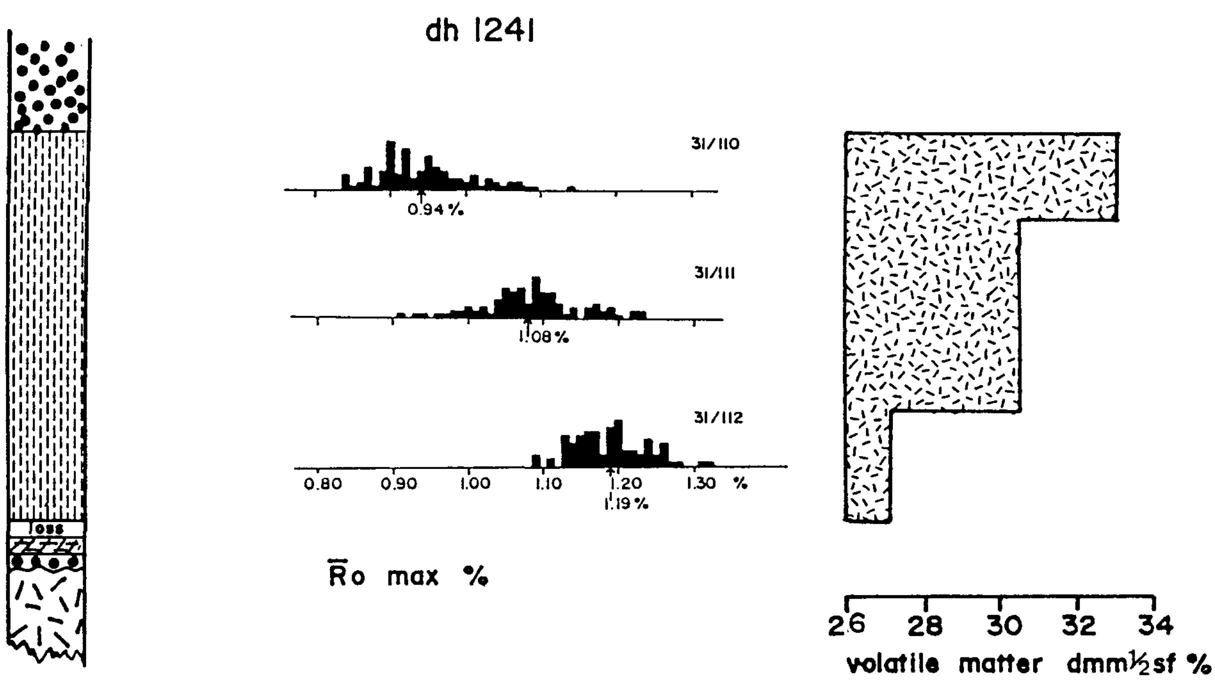


FIGURE 136. Typical examples of Webb/Baynes Brunner seam profiles showing inversely related trends in volatile matter and vitrinite reflectance.

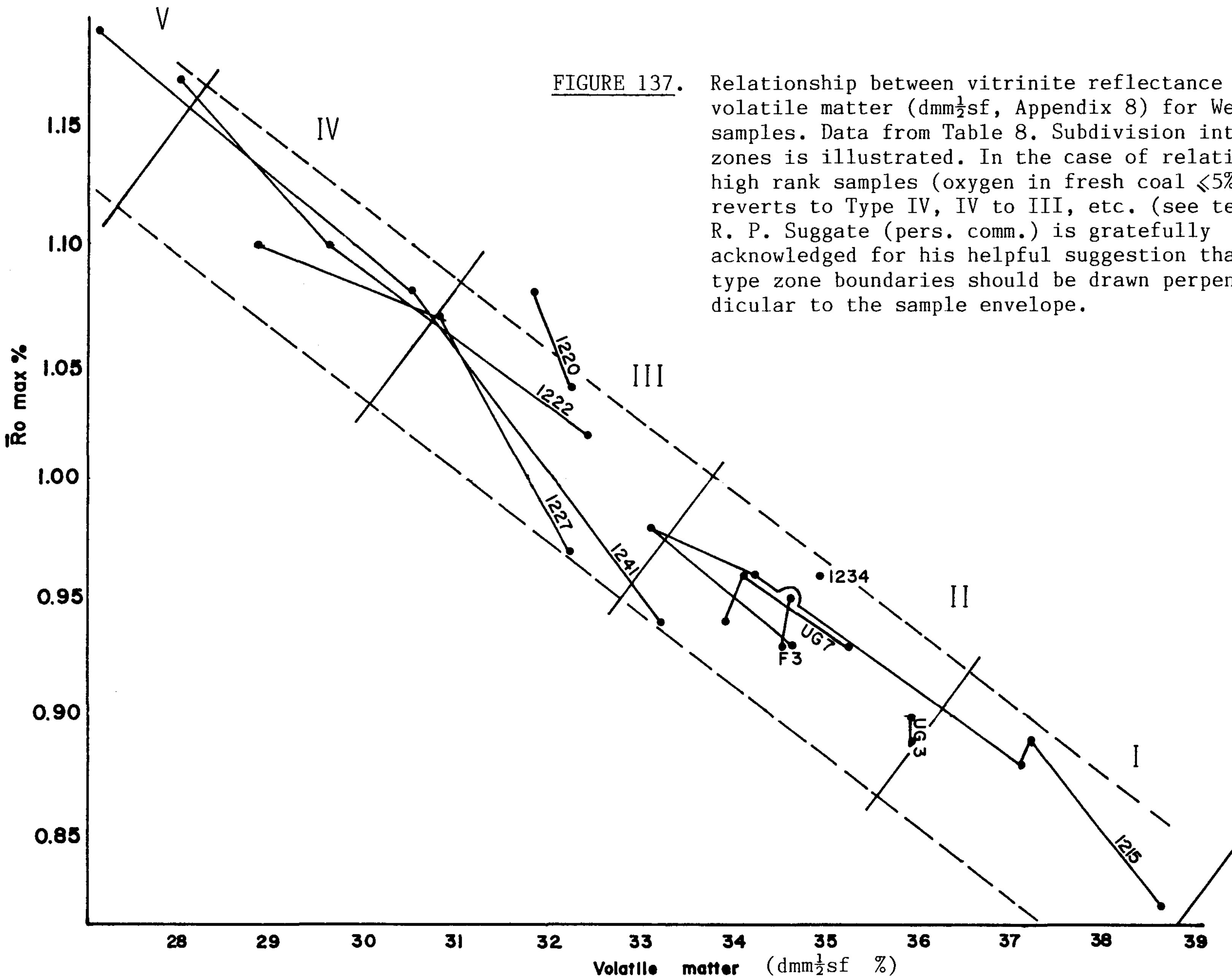


FIGURE 137. Relationship between vitrinite reflectance and volatile matter (dmm½sf, Appendix 8) for Webb/Baynes samples. Data from Table 8. Subdivision into type zones is illustrated. In the case of relatively high rank samples (oxygen in fresh coal ⩽5%) Type V reverts to Type IV, IV to III, etc. (see text). R. P. Suggate (pers. comm.) is gratefully acknowledged for his helpful suggestion that type zone boundaries should be drawn perpendicular to the sample envelope.

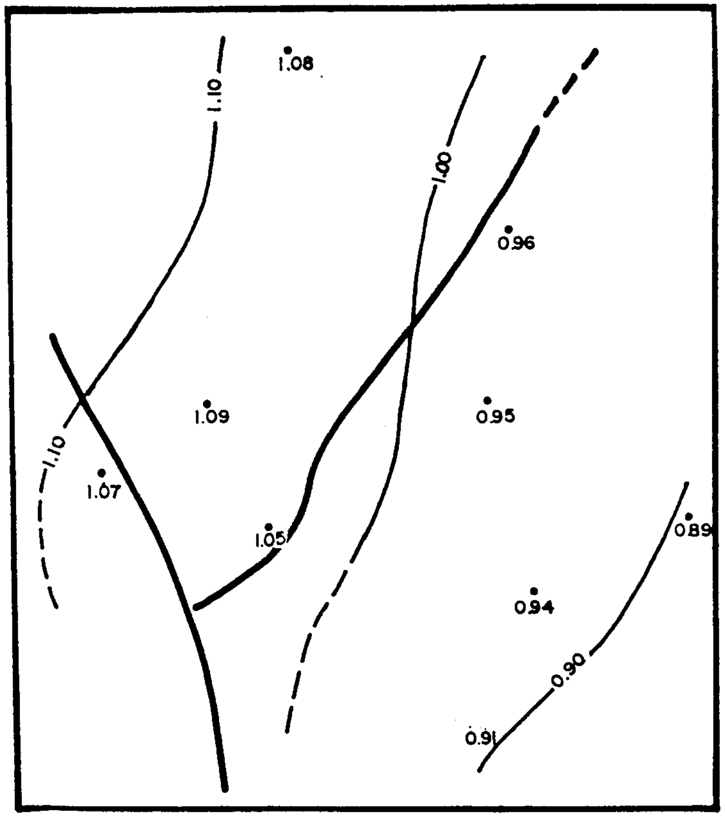


FIGURE 138. Lateral trends in vitrinite reflectance in the Brunner seam, Webb/Baynes Block, expressed on a whole seam weighted average.

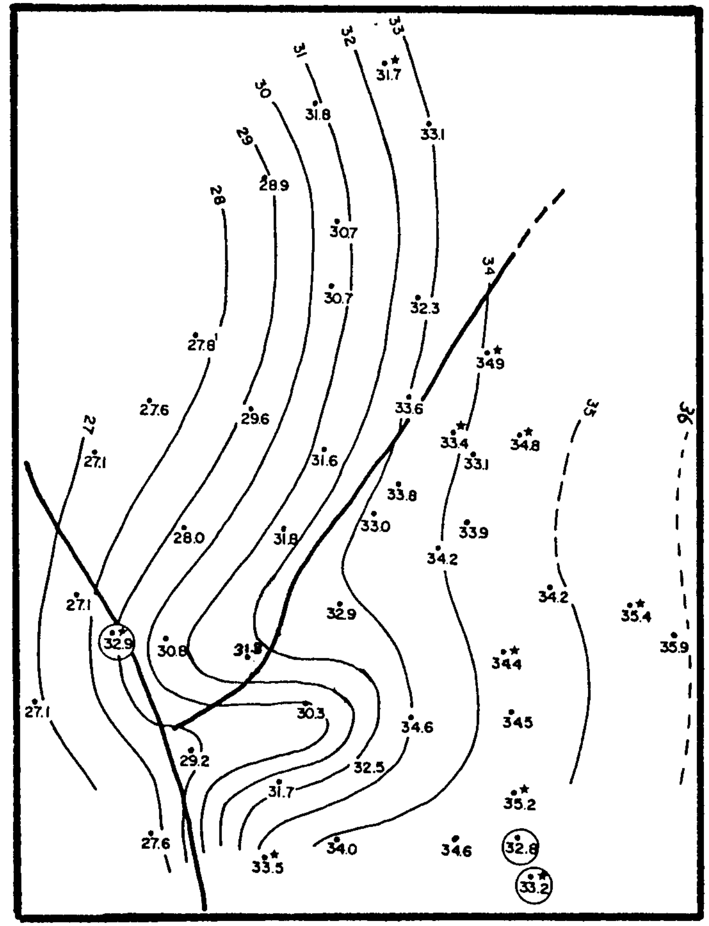


FIGURE 16. Lateral trends in volatile matter (dmm$\frac{1}{2}$sf, Appendix 8) in the lower part of the Webb/Baynes Brunner seam. The plot is restricted to basal composites where possible in an attempt to illustrate a more or less contemporaneous interval. Samples marked with stars represent the entire seam profile (where spanned by a single composite). Samples falling more than 1.5% outside the contour pattern are circled.

matter of *approximately* 6% (dmm½sf). Consequently the effects of type and rank change will be cumulative, because expected lateral trends to a lower volatile type approximately parallel lateral increases in rank. The lower part of the Webb/Baynes seam, which is assumed to comprise coal which accumulated more or less contemporaneously throughout the area, exhibits a lateral increase in volatile matter (VM) of approximately 9%, substantially more than could result from the expected rank increase. I believe that the c. 3% difference (c. Δ3%) which is not accounted for by rank changes represents type variation resulting from lateral variability in swamp drainage. Serial samples exhibit a larger vertical ΔVM of up to 6%. This discrepancy suggests that of the three swamp settings that are inferred to have existed, i.e., remote from open water/well drained, adjacent to open water/very poorly drained, and intermediate, the most poorly drained zone did not occur within the study area when peat accumulation was in its early stages, as in Figure 139. Coals representing the most poorly drained zone should occur to the northwest and south of the samples which have been studied, i.e., adjacent to the barren zones, where the seam may be very thin and/or split.

Whereas the basal coal is inferred to have accumulated in a range of swamp settings, the diachronous top of the seam appears likely to have accumulated under relatively uniform poorly drained conditions, in cases where accumulation ceased due to transgression of the lagoon/bay shoreline across the swamp. However, where accumulation was terminated by the fluvial event (4.6.2 (b)), roof coal may represent relatively well drained peat (e.g. Drillhole 1222), particularly if erosion of peat occurred. Volatile matter values for roof coal range from 38½% (Drillhole 1215) in the southeastern low rank area to 32-33% in the western high rank area (various drillholes), a difference of c.6% i.e., the value believed to result from rank variations as discussed previously, which confirms the supposition that highest volatile samples in the west and east represent coal of similar type and depositional setting.

The vitrinite reflectance/volatile matter band in Figure 137 is divided into 5 zones, I to V, representing very poorly drained (I) to very well drained (V) peat. (In practise, Type number V is not utilised, as explained below.) Because the $\overline{R}o$ max/VM band incorporates both rank and type variability, some adjustment is necessary to allow for rank when allocating a type number to any sample. Working on the basis that rank variation accounts for 6% of the observed

ΔVM, "high rank" western samples are demoted by one type number (= c. 6%). For example, ply 1 in Drillhole 1241 is demoted from Type II, within which zone it falls on Figure 137, to Type I. The 2 samples in zone V are both high rank, hence demoted to Type IV. Rather than using simple western versus eastern geographic demarcation, coals inferred to have $\leqslant$5% oxygen (dasf) when unweathered are inferred to be significantly higher rank than unweathered coals with 5-6% oxygen (see page 225), and such samples are demoted one Type number. Although this manipulation is arbitrary, it is considered to be satisfactory for the work in hand.

Where reflectance is not available, Type numbers are allocated on the basis of volatile matter yield alone (Fig. 140). Due to the width of the $\overline{R}o$ max/VM band there is overlap in the volatile matter ranges for adjacent type zones, so that 2 Type numbers must sometimes be allocated in Table 8 (e.g., Type II/III). Type numbers allocated using both reflectance and volatile matter data appear in Figure 141, which illustrates the vertical and lateral distribution of Type numbers in cross-section.

A number of maceral characteristics in addition to vitrinite reflectance exhibit variability within the study area. For example, exinite tends to be least abundant towards the bottom of seam intersections and in a regional sense least abundant in the west (Fig. 142a). The maceral exhibits an overall relationship with Types I to III (Table 9). Indeterminate vitrinite shows opposite trends (Fig. 142b), increasing as reflectance increases and volatile matter decreases, while exinite varies in the opposite sense. These trends are consistent with the paleoenvironmental model whereby Type I coals accumulated in poorly drained, poorly oxygenated circumstances, which would result in relatively good preservation of biodegradable exinite and vitrinite precursors (Fig. 143a). At the other extreme, Type III coals are postulated to have accumulated in well drained and relatively oxygenated environments, which would tend to result in some decay of exinite and vitrinite precursors and loss of definition between vitrinite macerals (Fig. 143b). Exinite precursors are generally regarded as rather stable even in oxidising conditions, but some elements may not be, pollen for example, which may have been an important source of liptodetrinite in Webb/Baynes coals. Although regional variations in exinite and indeterminate vitrinite can be explained in terms of type variation, the potential for westward

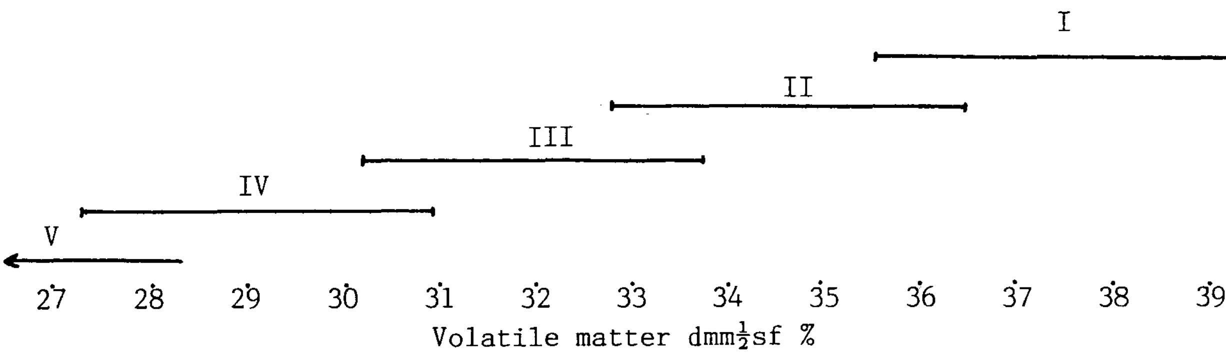


FIGURE 140. Allocation of coal type numbers on the basis of volatile matter (dmm$\frac{1}{2}$sf), as derived from the $\bar{R}o$ max/VM envelope in Figure 137. In the case of relatively high rank samples (oxygen $\leqslant$ 5% in unweathered coals) Type V reverts to Type IV, Type IV reverts to Type III, etc.

rank increase to influence apparent maceral proportions is acknowledged. With increasing rank the contrast between macerals diminishes, however it is questionable whether Webb/Baynes coals attain ranks where distinction between exinite and vitrinite, and between desmocollinite and telocollinite, is significantly impaired. Maceral analyses are interpreted here as if maceral proportions are unaffected by rank.

The significance of regional variations in most macerals other than exinite and indeterminate vitrinite is obscure. Vitrodetrinite is generally sparse except in the southeast (Fig. 142c), where it ranges up to 15% in a zone which appears independent of any other maceral or obvious paleoenvironmental factor. Vitrodetrinite consists of small vitrinite fragments which can originate by mechanical fragmentation of plant tissues, for example by reworking of plant debris during flooding of a swamp. The high vitrodetrinite zone at Webb/Baynes, however, coincides with a very low ash area implying little flooding and a more likely origin of the maceral is by passive disintegration of certain plant tissues into component cells with gelled or solidified cell contents. Virtual restriction of the vitrodetrinite maceral to a well defined southeastern zone may reflect localisation of a particular floral type to that area, or alternatively some feature of swamp chemistry as yet undisclosed. Paucity of vitrodetrinite in the west may to an unknown extent result from inclusion of the

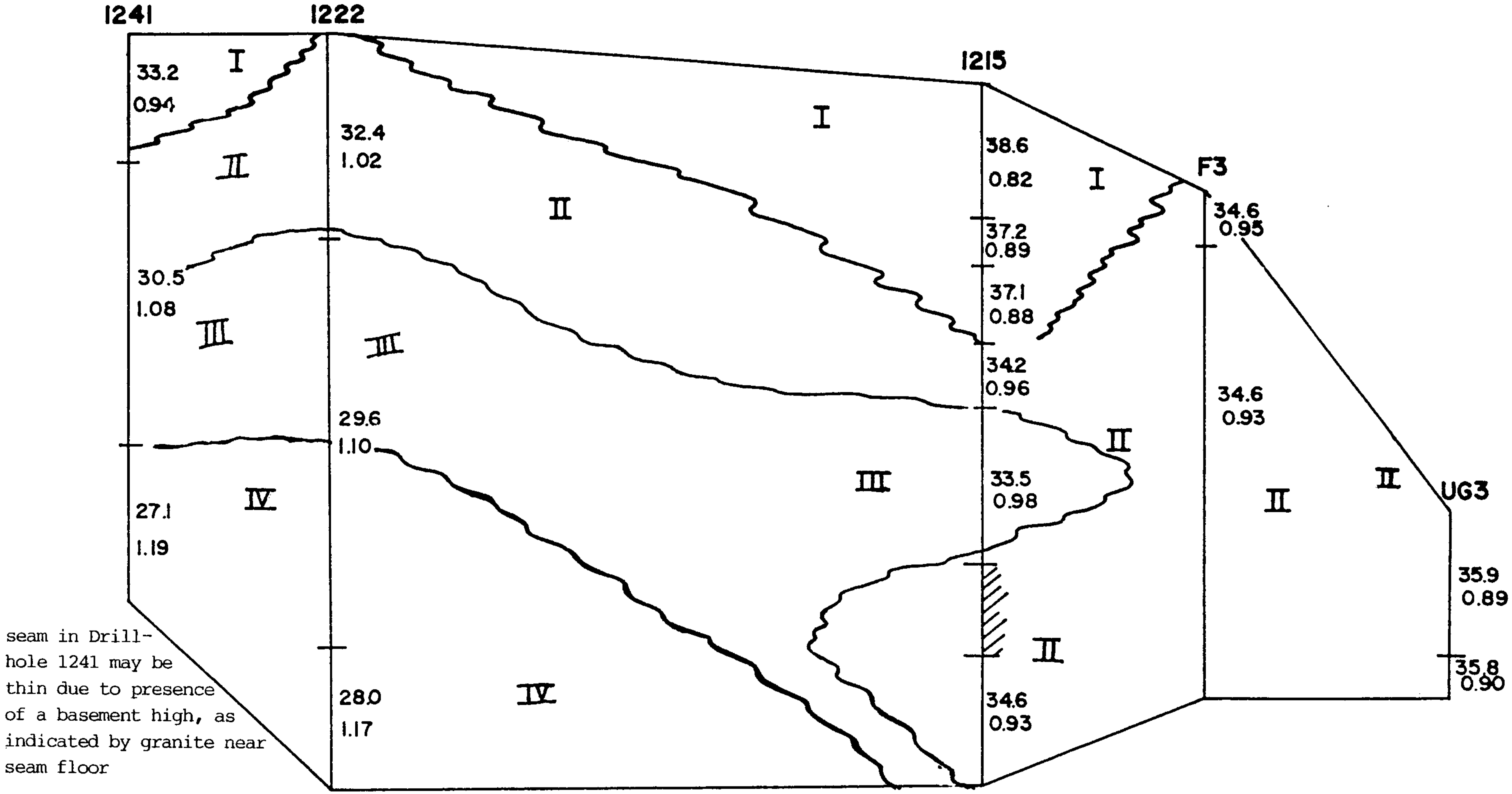
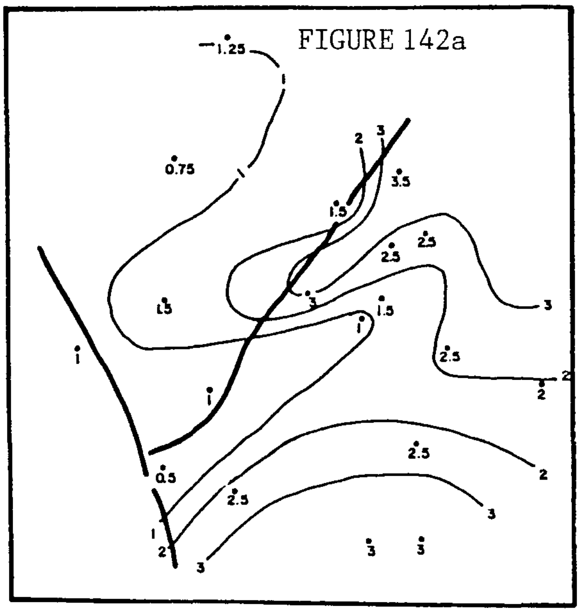
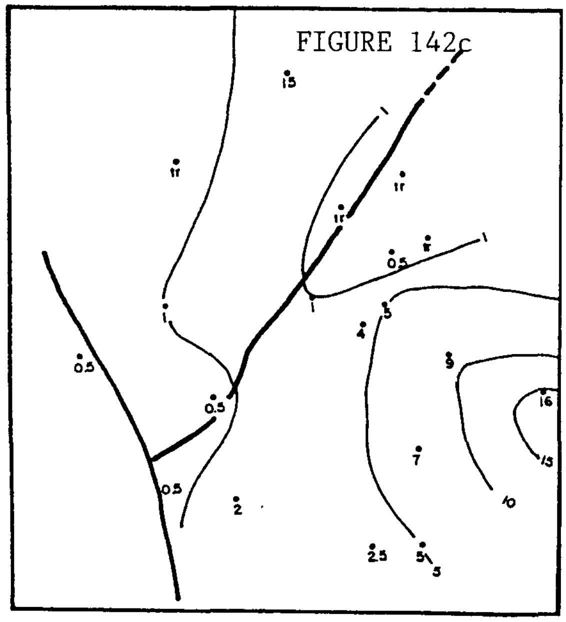
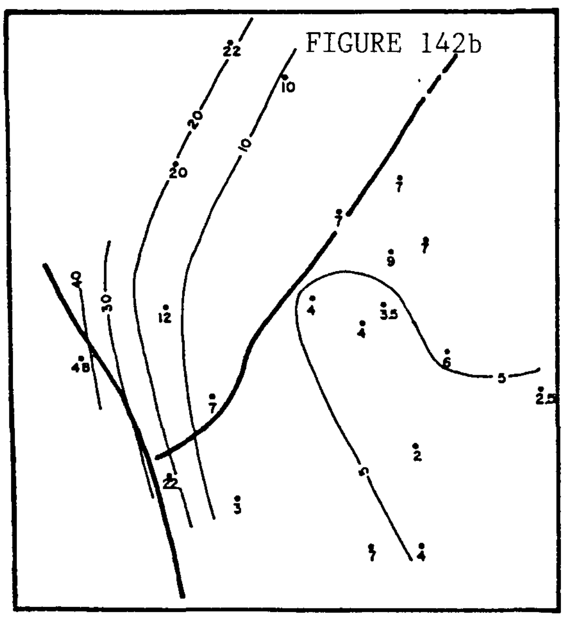


FIGURE 141. Vertical and lateral distribution of coal Type numbers I to IV across the Webb/Baynes area. Vertical lines show seam intersections subdivided into composites for which volatile matter (% dmm$\frac{1}{2}$sf) and vitrinite reflectance (%) are given.







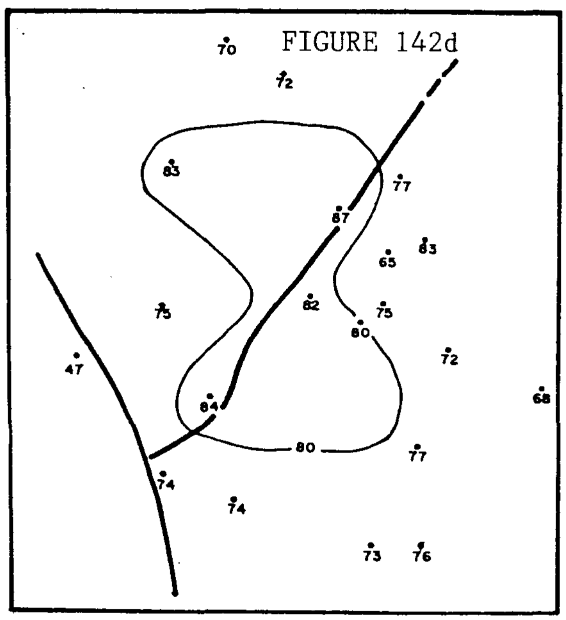


FIGURE 142a. Lateral trends in exinite in the Brunner seam, Webb/Baynes Block.

FIGURE 142b. Lateral trends in indeterminate vitrinite in the Brunner seam, Webb/Baynes Block.

FIGURE 142c. Lateral trends in vitrodetrinite in the Brunner seam, Webb/Baynes Block.

FIGURE 142d. Lateral trends in desmocollinite in the Brunner seam, Webb/Baynes Block.

All in % on a whole seam weighted average basis, mineral matter free.

FIGURE 143a.

Good definition within and between vitrinite macerals in a Type II coal. Exinite (E) is represented. Sample 31/061, UG7, horizontal field 0.15mm.

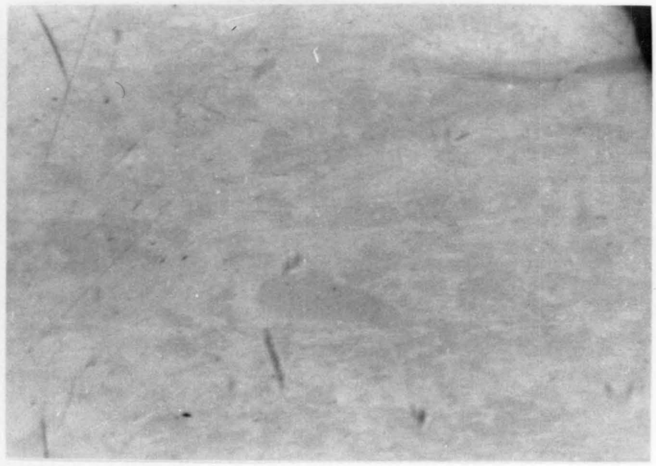


FIGURE 143b.

Poor definition within and between vitrinite macerals in a Type III coal. Exinite is not represented. Sample 31/112, drillhole 1241, horizontal field 0.25mm.

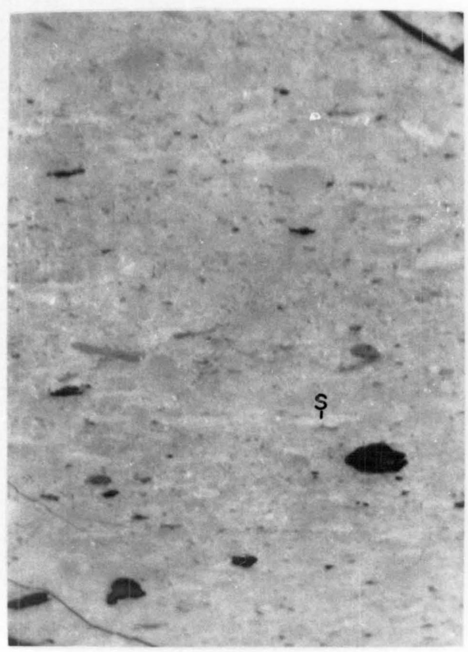


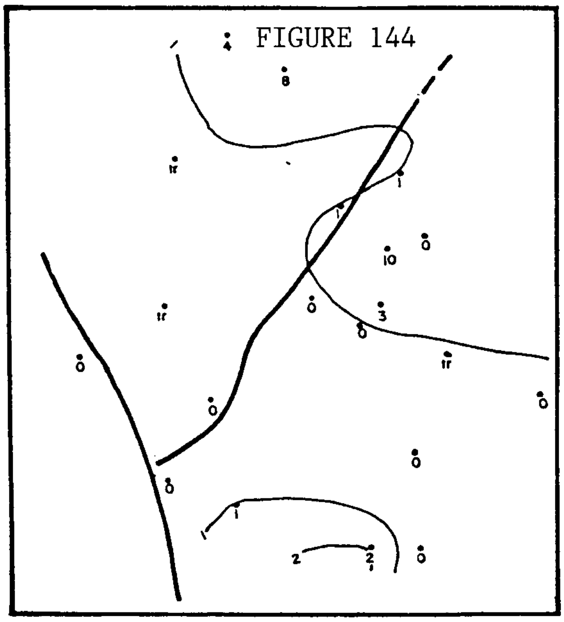
FIGURE 143c.

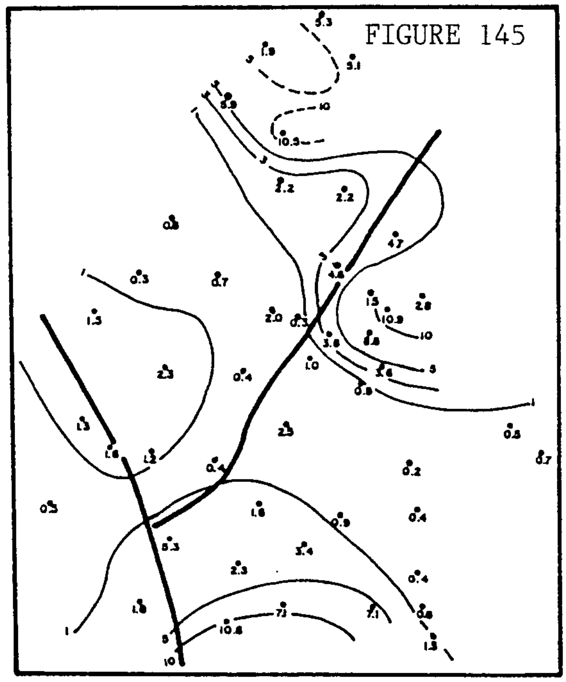
Typically fine 'wispy' semifusinite (S). Sample 31/050, UG3, horizontal field 0.15mm.

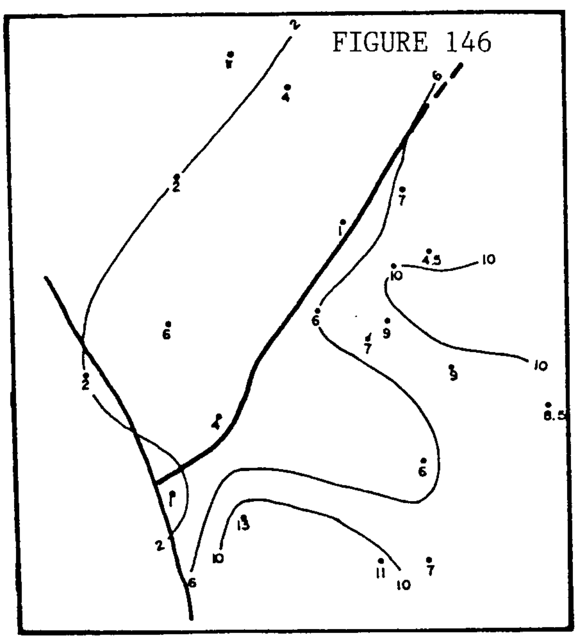
maceral in indeterminate vitrinite, due to poor contrast between vitrinite macerals in most Type III coals, however this cannot explain the paucity of the maceral in most areas dominated by Type II coals. A general correspondence of particularly low indeterminate vitrinite values with the high vitrodetrinite zone is inferred to indicate the influence of some common factor on both macerals, rather than an inevitable obscuring of vitrodetrinite elsewhere by indeterminate vitrinite. This distinction is supported by the fact that there is insufficient indeterminate vitrinite present in eastern areas to accommodate 10-15% vitrodetrinite.

Desmocollinite variability (Fig. 142d) is not a particularly useful indicator of peat swamp conditions, partly because the increase which could be expected in better oxygenated areas is obscured by a marked increase in indeterminate vitrinite in such areas. Vitrinite intercalated with mineral matter (Fig. 144) occurs in significant amounts only where part of the seam is dirty (Fig. 145), as expected. Telocollinite (Fig. 146) is sparse in the west, perhaps because it cannot be distinguished and is part of indeterminate vitrinite, or it may genuinely be present in only small amounts. If the latter, possible reasons are insufficient nutrient supply to support woody plants in the raised bog area (as postulated for certain coals in the Rapahoe Sector in Greymouth), and/or decomposition of woody tissue to desmocollinite under relatively well oxygenated conditions in the west. Telocollinite approaches 10% only in areas influenced by flooding, which supplies mineral matter and nutrients, and these areas are also interpreted to have been poorly drained and hence poorly oxygenated, inhibiting decomposition of plant debris.

Inertinite is present as semifusinite, which in the Webb/Baynes coals is frequently little more reflective than vitrinite. Much of the semifusinite is a fine, 'wispy' material (Fig. 143c) which probably originated as partially oxidised shreds of plant debris generated above water level in the swamp, and also washed and blown into the swamp from peripheral areas. A significant proportion of the semifusinite has a structure consistent with derivation from fragmented fungal material (sclerotinite), but this origin is rarely certain, partly due to poor preservation and also because oxidised plant tissues, particularly roots and stems, can resemble fungal material. Consequently only a small proportion of fungal-like material can be reliably classified as sclerotinite in a maceral analysis.







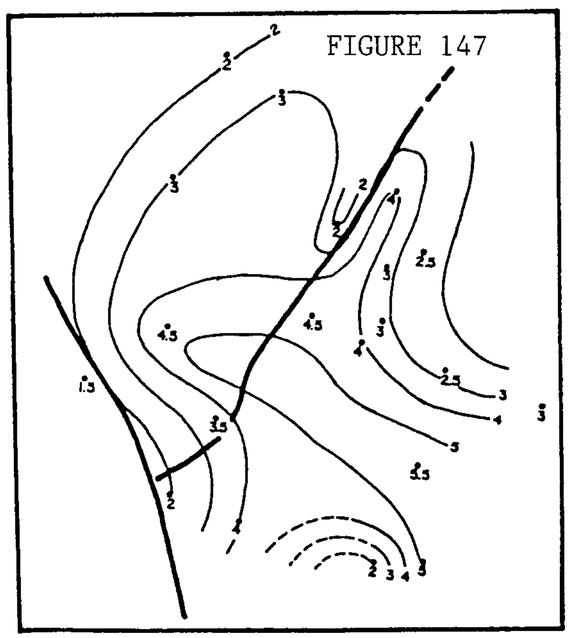


FIGURE 144. Lateral trends in vitrinite intercalated with mineral matter in the Brunner seam, Webb/ Baynes Block.

FIGURE 145. Lateral trends in ash content (dry basis) in the Brunner seam, Webb/Baynes Block.

FIGURE 146. Lateral trends in telocollinite in the Brunner seam, Webb/Baynes Block.

FIGURE 147. Lateral trends in inertinite in the Brunner seam, Webb/Baynes Block.

All in % on a whole seam weighted average basis.
Figures 144, 146 and 147 mineral matter free.

Variations in inertinite content within the study area (Fig. 147) show some interesting trends. Very low values in the west probably result from the generally poor contrast between macerals in Type III coals. Relatively advanced oxidation of vitrinite precursors during peatification appears to have closed the gap in reflectance between vitrinite and semifusinite in these coals (Fig. 148), whereas in Type I & II coals there is a small but discernable distinction (Fig. 149) attributed to poorer swamp oxygenation and hence lower oxidation of vitrinite precursors. This interpretation implies that much 'vitrinite' in Type III coals has similar composition to much 'semifusinite' in Type I & II coals, a conclusion which is consistent with the remarkable potential for variability in volatile matter and reflectance of isorank vitrinites from serial samples in the study area, and which is supported by Nuclear Magnetic Resonance studies (S J Davenport, pers. comm.). The tendency for poor semifusinite distinction to depress inertinite values determined for the lower part of individual seam profiles is obscured because inertinite also tends to be low in upper parts of the seam, due to a decline in inertinite generation as the swamp was drowned.

In the east and southeast, inertinite values correlate inversely with ash content, i.e., inertinite is highest where the coal is very clean and declines as the coal becomes dirtier (Figs 145 & 147). The simplest interpretation of these trends is that the southeastern low ash zone was relatively well drained, with a small contribution of mineral matter by floods and a greater probability that oxygenation of the peat surface would produce semifusinite. Conversely, the peat surface was more consistently saturated northeast and southwest of the low ash/high inertinite zone, with the result that plant debris was less likely to be oxidised sufficiently to produce semifusinite.

This discussion of variations in volatile matter, reflectance, and maceral characteristics has been kept as brief as possible consistent with achieving an adequate interpretation, and little attempt has been made to discuss small deviations from the suggested relationships. A more detailed study would permit a deeper understanding of paleoenvironmental influence on coal characteristics in the Webb/Baynes area, but would require investigation of the maceral characteristics and preferably also the reflectance of all available samples, not merely the suite selected for the current investigation. Enlargement of the data base would result in more precise definition of

Type Zone	Exinite abundance by sample (mineral matter free)
I	2, 2½, 3½, 3, 3½, 1, 1,
I/II	2½, ½, 1, 2½, 2½,
II	1½,2½,2½,1,1½,1,½,2½,2½,1,2,3½,1,2½,½,1,1,3,tr,1½, 2,1,1½,½,3½,2½,1,
II/III	3,½,2,3½,
III	2,½,½,1,1,tr,1,1,½,1,½,

Statistics	Average	Sample No.	Standard deviation
I	2½	7	1
I/II	2	5	1
II	1½	27	1
II/III	2	4	1½
III	1	11	½

TABLE 9. Relationship between exinite abundance and type zone or number using data from Table 8 treated mathematically. Exinite declines with increasing type number.

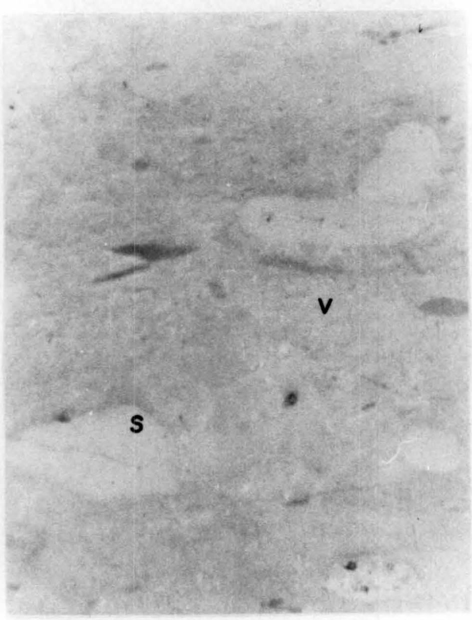


FIGURE 148.

Poor distinction between semifusinite (and vitrinite (V) in a Type III coal. Sa 31/112, drillhole 1241, horizontal field 0.15mm.

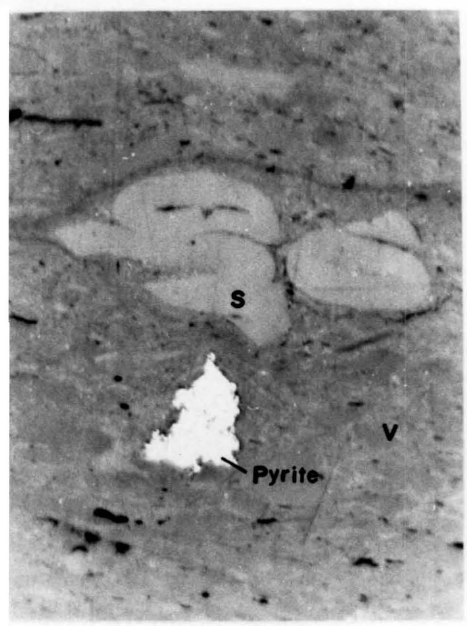


FIGURE 149.

Good distinction between semifusinite and vitrinite in a Type I coal. Sample 31/050, UG3, horizontal field 0.15mm.

distribution patterns for the various macerals, and if the formula for correction of volatile matter to a dry mineral matter and sulphur free basis can be improved (Appendix 8), and more reflectance determinations obtained, the distribution and significance of the different types could be more accurately delineated. In order to examine the history of swamp development in detail it would be desirable to plot volatile matter, reflectance, maceral characteristics, mineral matter, etc. successively for intervals of the seam which accumulated early in swamp development, at an intermediate stage, and late in swamp development, as far as correlation of sections permits definition of these chronological intervals. The present method of using weighted values for whole seam intervals is likely to obscure several relationships which are better studied over a shorter interval.

(d) Conclusion. Consideration of all pertinent seam characteristics, including those discussed in 4.6.2, suggests that a raised bog environment predominated in the west, extending into the southeast as an arm between poorly drained areas. This distribution is indicated by many seam characteristics, particularly ash, inertinite, telocollinite, and volatile matter (dmm$\frac{1}{2}$sf) if plotted for a restricted interval such as the lower part of the seam. Seam thickness, and distribution and thickness of the marginal marine facies interval which overlies the seam, also support this paleogeographic reconstruction. The model has been defined in general terms, and local departures by some properties from expected trends may indicate a complexity in the original depositional environment which is not accommodated by the model. For example, syndepositional faulting may have influenced seam thickness. Other limitations have been discussed above.

4.6.4 Other coal properties

(a) Sulphur. On a whole seam basis (dry ash free), sulphur within the study area ranges from less than 1% to more than 3% (Fig. 150). Sulphur variations in individual seam intersections follow two main profiles in unweathered examples (Fig. 151a & b). There is considerable lateral variability in sulphur levels at the top of the seam (<1 - >5%), and this appears to be broadly related to roof lithology as observed by earlier workers. Figure 152 shows contoured sulphur values for the top c.2m of each seam intersection, derived as a weighted average from ply analyses. Figure 153 shows the thickness of mudstone constituting the immediate roof of the

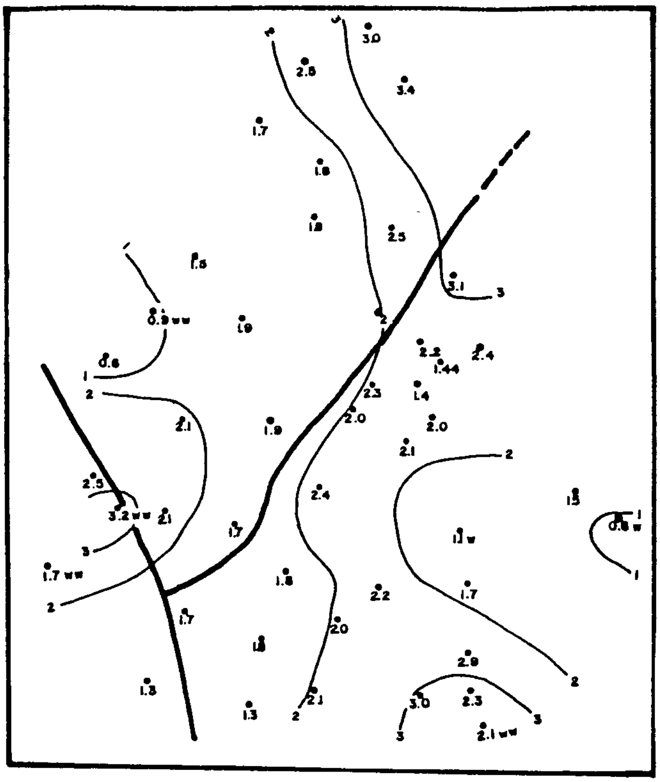


FIGURE 150. Lateral variations in sulphur in the Brunner seam, Webb/Baynes Block. (Dry ash free, whole seam weighted average).

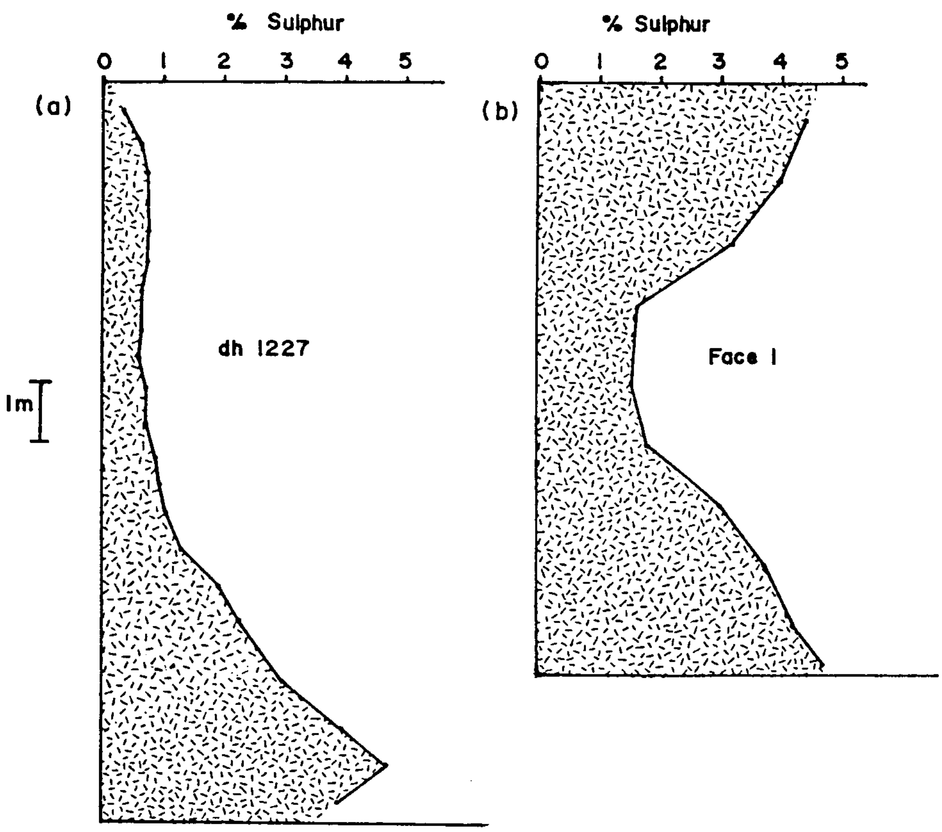


FIGURE 151. Typical examples of sulphur variation in unweathered Brunner seam profiles, Webb/Baynes Block (dry, ash free).

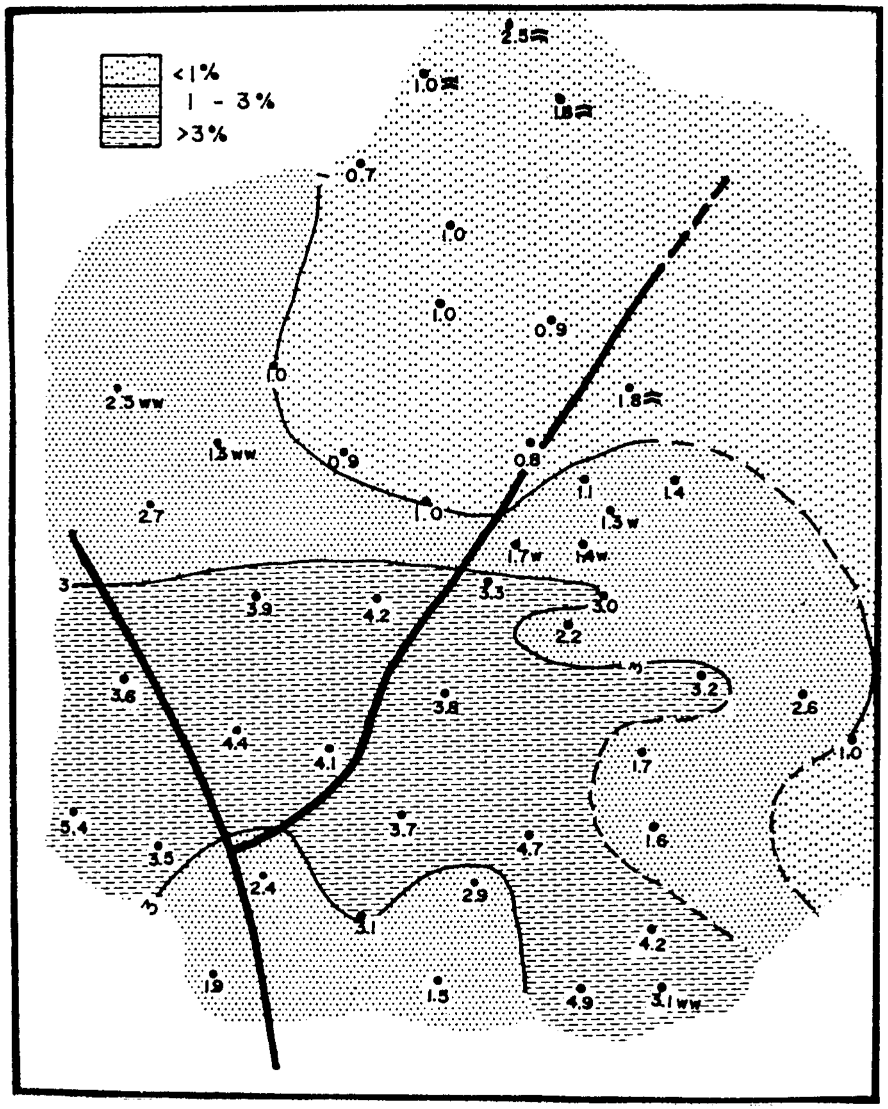


FIGURE 152. Lateral trends in sulphur in the top c. 2m of the Brunner seam at Webb/Baynes Block (dry ash free, weighted average from ply analyses). w = weathered ww = very weathered. ≋ indicates sulphur enrichment from below, rather than via the seam roof.

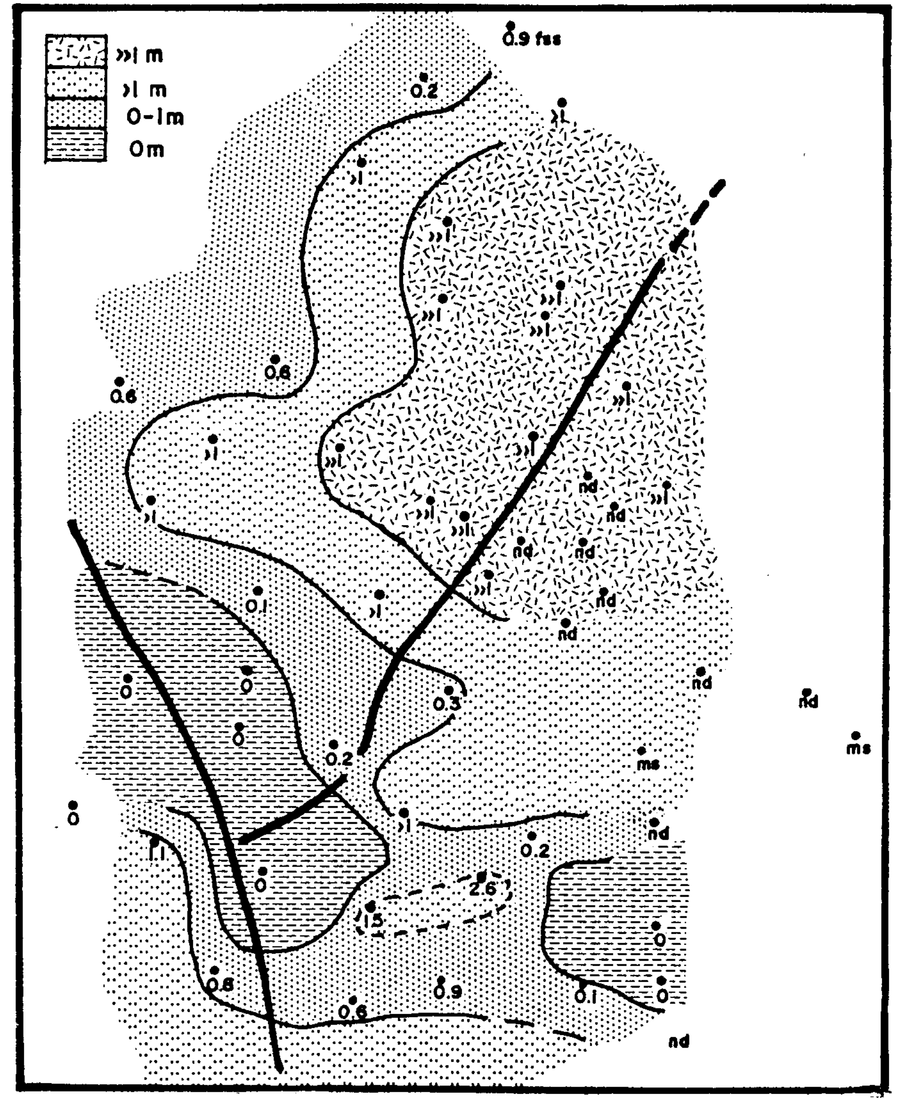


FIGURE 153. Webb/Baynes Brunner seam roof lithology, expressed as metres of mudstone separating coal from overlying permeable sandstone strata. ms = mudstone roof but no thickness data available.

seam. The resulting patterns show good correspondence within the limitations imposed by this very simplified characterisation of roof lithology, and confirm that sulphur enrichment of the upper part of the seam is largely a function of roof permeability, sandstones being more permeable than mudstones. Peat is relatively impermeable, especially after compaction under overlying sediments, and sulphur is consequently low (often $\leqslant$1%) in central plies, particularly where the seam is thick. Pyrite also tends to be relatively sparse in central plies for the same reason.

Sulphur levels in the lower few metres of the seam (Fig. 154) are uniformly high (>3%) except in weathered samples, and do not exhibit a close relationship with floor lithology (Fig. 155) except in a northeastern zone. This zone, where the lower part of the seam has >4% sulphur, coincides with a floor of sandstone and sandstone overlain by thin mudstone. In this particular area, where the seam roof is thick mudstone, the seam is relatively thin and permeation upwards from the floor has resulted in moderately high sulphur values even at the top of the seam (e.g., Drillhole 1242 Fig. 156). The progressive upward decline indicates that little sulphur has been introduced via the impermeable roof.

Generally high sulphur levels in the lower part of the seam, irrespective of floor lithology, may be due to migration of sulphur-bearing solutions under some pressure in the confined space between the seam and impermeable basement rocks. Solutions affecting the coal from above were evidently not subject to such confinement and sulphur enrichment more clearly reflects the natural permeability of the roof sediments.

There is no evidence that sulphur variations observed in the Webb/Baynes area result from syndepositional enrichment as a consequence of marine influence during peat accumulation. Syndepositional sulphur enrichment may occur elsewhere in the Buller Coalfield, however, and is considered to have influenced some Brunner coals at Pike River Coalfield (see 4.5.3).

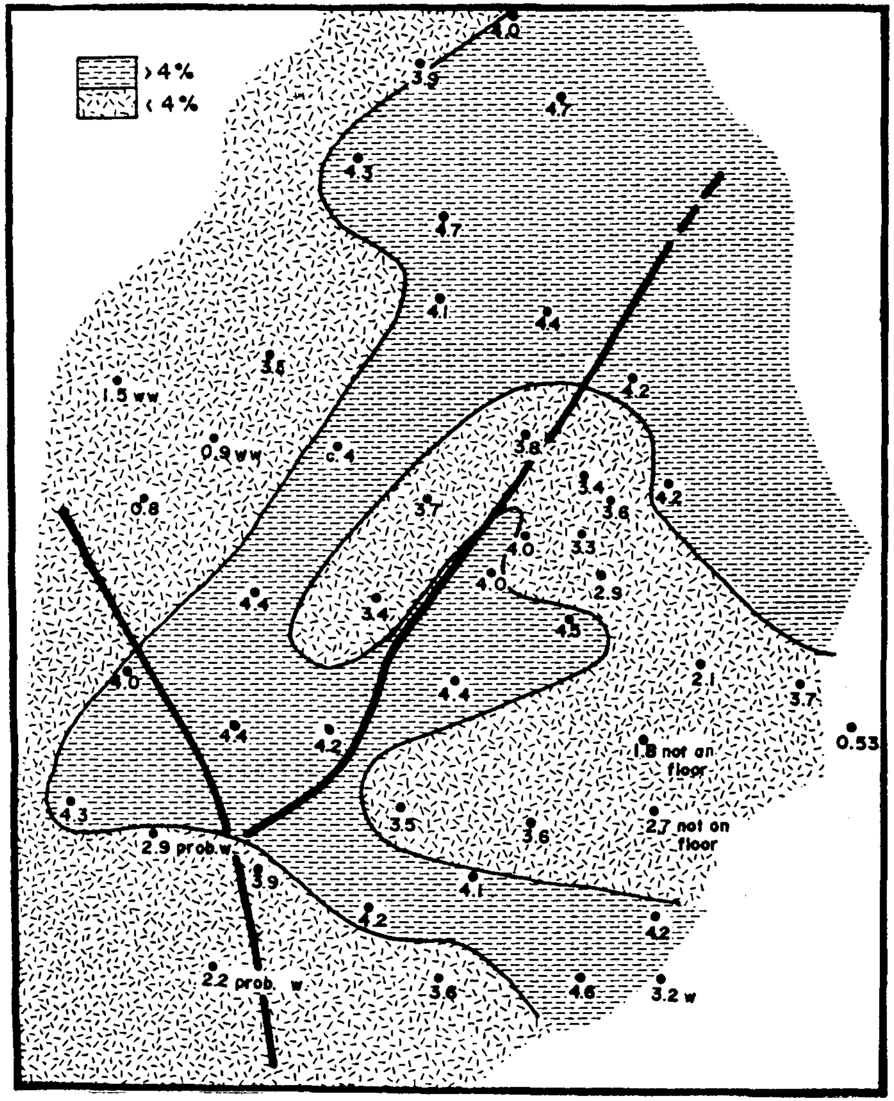


FIGURE 154. Lateral trends in sulphur in the lower c. 2m of the Brunner seam, Webb/Baynes Block (dry ash free basis, weighted average from ply analyses.) w = weathered ww = very weathered. 'not on floor' indicates that basal, high sulphur coal was not available for inclusion in sample.

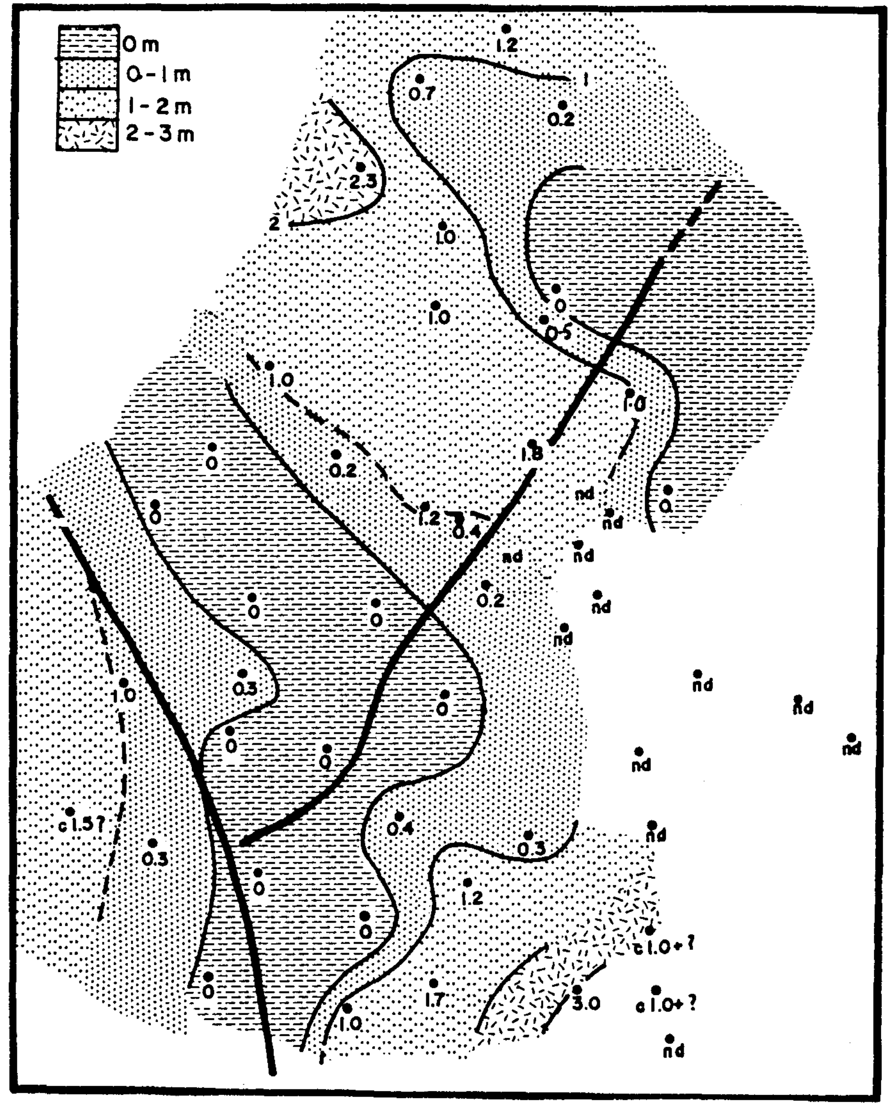


FIGURE 155. Floor lithology of the Brunner seam at Webb/Baynes, expressed as metres of mudstone separating the coal from underlying permeable sandstone strata.

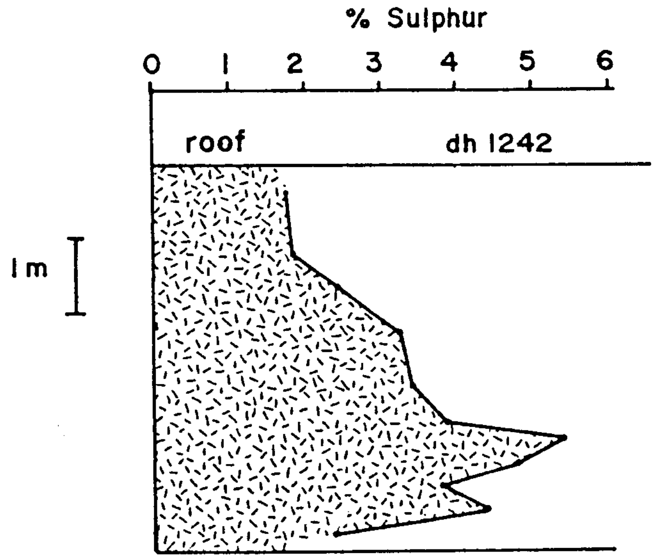


FIGURE 156. Sulphur variation within the Drillhole 1242 Brunner seam profile, Webb/Baynes Block (dry ash free basis). The sulphur gradient suggests enrichment via the seam floor, rather than the roof.

(b) Carbonisation behaviour. As discussed in Section 4.5.3, carbonisation behaviour is dependant on both coal rank and type. In many overseas coals the relationship with type is a simple function of maceral proportions, but in West Coast coals the important variable is vitrinite chemistry, which can vary substantially between different coals of the same rank (see 4.2).

Discussion of carbonisation properties in Webb/Baynes coals is here restricted to fluidity, which in the study area varies throughout the full measurable range in response to the combined effects of coal rank, coal type, and weathering. It is difficult to separate the influence of these three factors, however an attempt has been made. Figures 157 and 158 relate fluidity to volatile matter, using logarithmic and linear fluidity scales respectively. The former is mainly useful in the field below 5,000 ddm (dial divisions per minute) and the latter for values 5,000 to 50,000 ddm (uppermost range of measuring equipment). In Figure 158 a broadly linear relationship (shown by an envelope) links the suite of samples which, at any particular volatile matter, have highest fluidity. Within this suite fluidity declines very rapidly as volatile matter decreases, a trend which is consistent with the effects of coal type variation postulated in Section 4.6.3, but which could also result from increasing

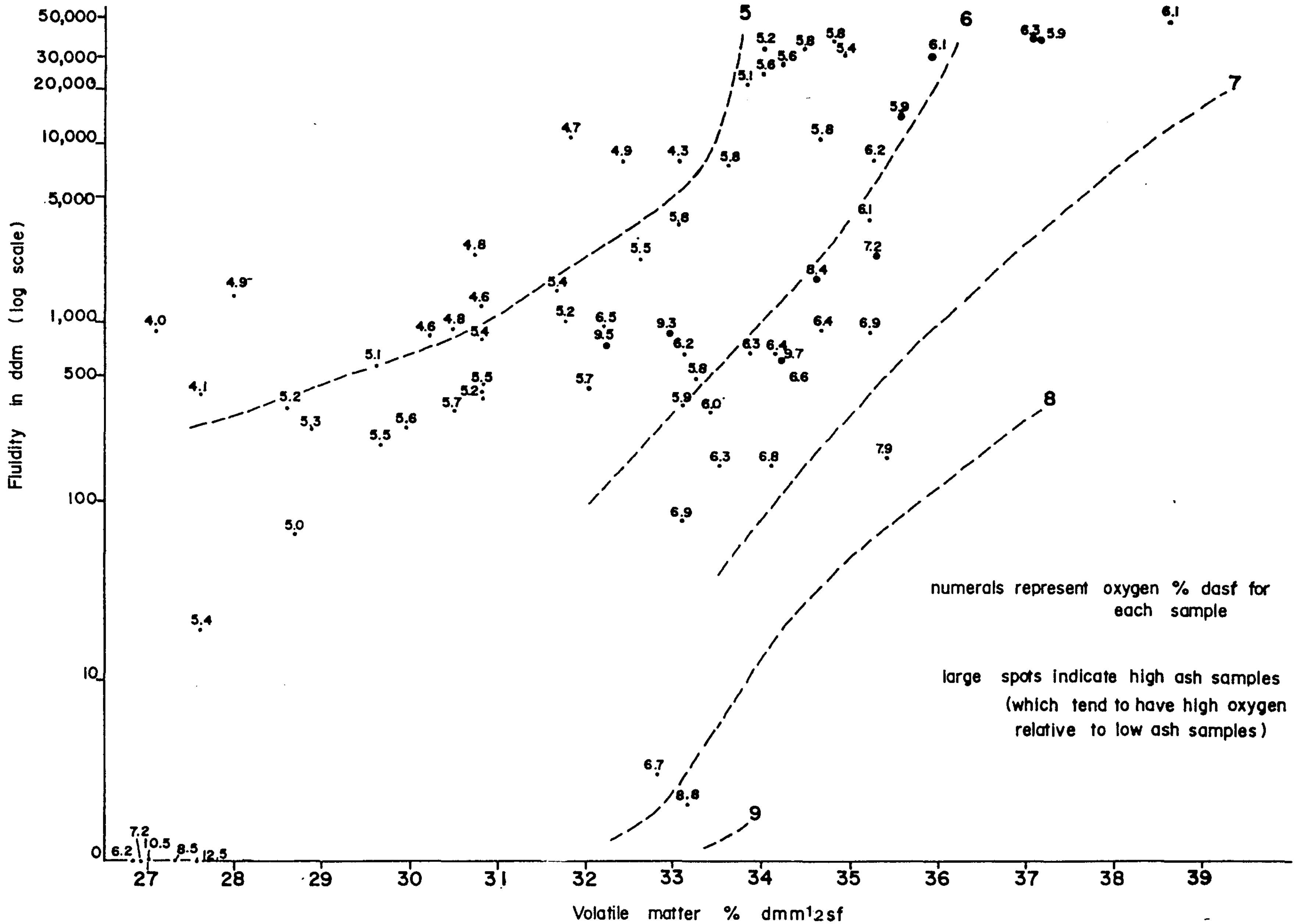


FIGURE 157. Plot of fluidity (log) against volatile matter for Brunner samples at Webb/Baynes Block.

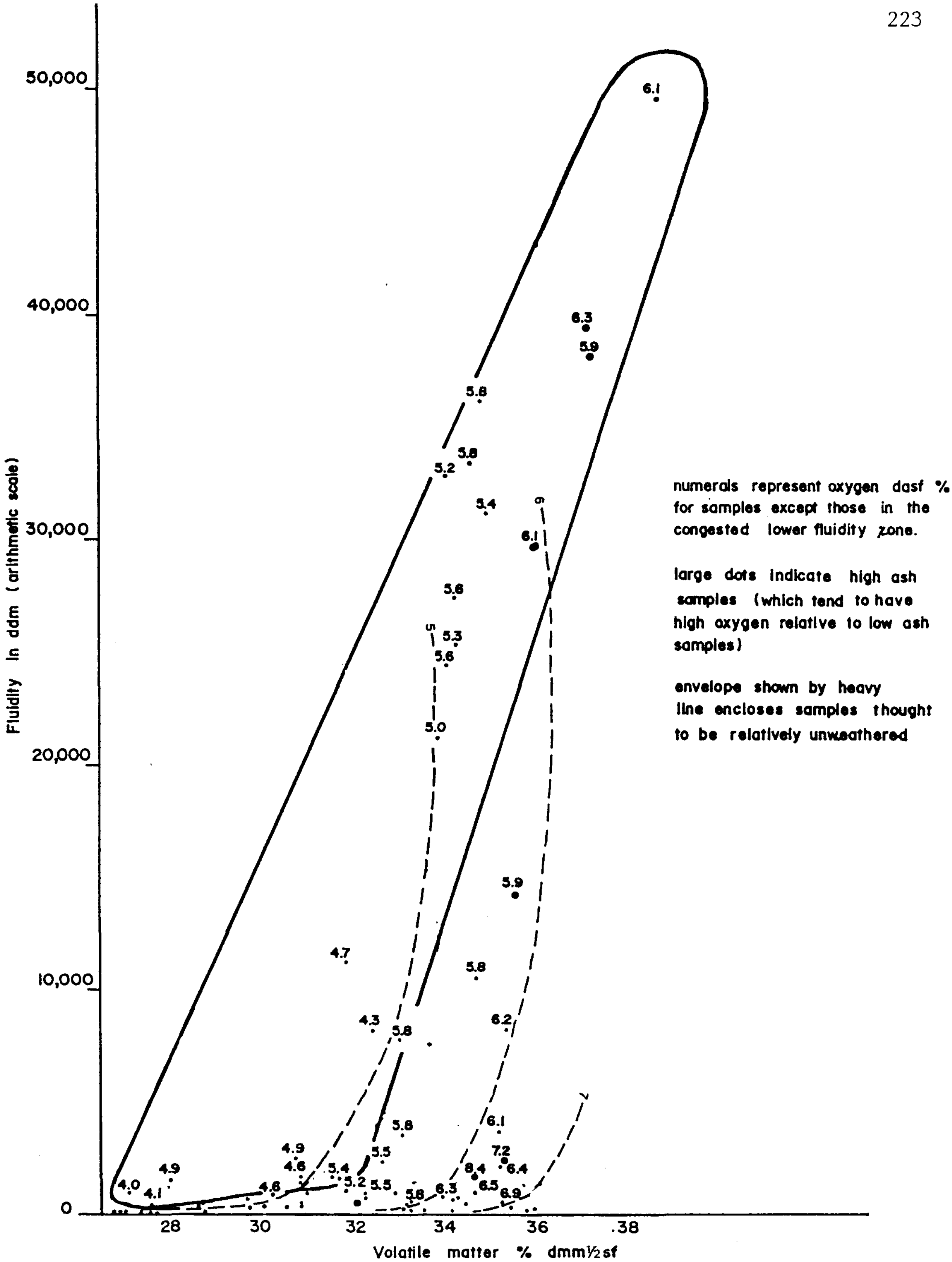


FIGURE 158. Plot showing a broadly linear relationship between maximum fluidity (normal scale) and volatile matter for relatively unweathered samples. Weathered samples fall below the linear envelope.

rank because the coals are approaching the critical stage where a small rank increase can profoundly reduce fluidity (Figure 159).

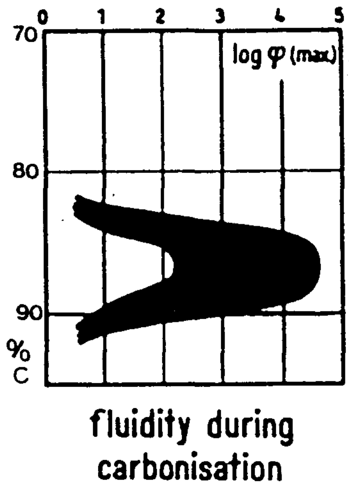


FIGURE 159. Variation in fluidity as a function of rank, represented by carbon content. Adapted from Stach et al. (1982).

In order to elucidate possible rank variation, oxygen (dasf) was plotted against sample points on Figures 157 and 158. In the case of serial samples of varying coal type, oxygen is expected to increase with increasing reflectance and decreasing volatile matter, and vice versa, representing variations in original peat oxygenation. These relationships are well defined and consistent in Brunner coals sampled during drilling at Pike River Coalfield (see 4.5.3) but cannot be independently confirmed for Webb/Baynes coals due to the effects of weathering, which causes a marked increase in oxygen. Conversely, oxygen declines as rank increases. Due to the combined effects of coal type, rank and weathering, patterns of oxygen variation in Figures 157 and 158 are likely to be complex. However, the progressive decline in oxygen within the linear envelope of highest fluidity on Figure 158 can only indicate a general tendency for rank to increase as volatile matter declines, i.e., variations in volatile matter, although partly a consequence of type variation (as shown by serial samples on Figure 137), are also partly a result of rank change.

Samples with ⩽5% oxygen in the envelope on Figure 158 are from Drillholes 1220, 1222, 1228, 1239, and 1241, all in the western part of the Webb/Baynes area. Other western samples plot in the very low fluidity zone beneath the envelope and have oxygen >5% due to weathering. A westward increase in rank is consistent with regional rank patterns documented by Suggate (1959) in his Figure 45 (see 4.6.3 (c)). These observations suggest that the relatively low fluidity of low volatile coals in Figure 158 is probably a response to both type and rank effects.

The relative importance of type and rank to fluidity is best demonstrated by serial samples with substantial variations in coal type at constant rank, and it is very unfortunate in this regard that so many of the samples are weathered. The seam intersection in Drillhole 1241, for example, exhibits striking variations in reflectance and volatile matter ranging from Type I at the top to IV at the bottom, but the fluidity gradient expected to accompany such variations is reversed because the coal is increasingly weathered towards the roof. Also in the low volatile end of the envelope (Figure 158) is sample 31/129 from Drillhole 1239, but unfortunately the fluidity of the upper part of this seam profile is not available for comparison. (A similar volatile matter content in these two samples suggests that there would in fact be little contrast in fluidity.) Fortunately there is a moderately fresh sample (31/083, Type II) paired with the low volatile (Type IV) sample 31/085 in Drillhole 1222. Sample 31/083 comprises the top several metres of the seam at this locality and exhibits substantially higher values for both fluidity and volatile matter than does 31/085, which is from the bottom of the seam (Table 8). Other paired analyses demonstrate this trend, but only where the samples are unweathered. In the case of 31/040 and 31/041 (Drillhole 1216), the upper sample has higher volatile matter, lower reflectance, and substantially higher fluidity than the basal sample (Table 8), and in the apparent absence of weathering these differences are attributed to type variation.

Beneath and to the right of the fluidity/volatile matter envelope (Fig. 158) lie many samples which have both lower than optimum fluidity and high oxygen in relation to their volatile matter content. These samples are considered to be weathered, and the more extreme the weathering the higher their oxygen, even after fluidity has declined to zero. Consequently, on a fluidity/volatile matter plot, iso-oxygen lines tend to cluster together and converge on the base-line.

Overseas workers have attributed some variations in fluidity to variations in the organic sulphur content of coals, and this approach has recently been applied to Buller coals (P. R. Gunn, pers. comm.). My experience with high sulphur coals at Buller and Pike River Coalfields indicates that aspects of vitrinite type independent of sulphur content are the principal influence on fluidity in unweathered isorank coals. Type gradients typically developed in the Brunner coals in question are such that volatile matter/vitrinite reactivity tend to increase upward in a seam, as does sulphur due to permeation from above. The consequent relationship between sulphur and fluidity is considered to be a result of these parallel trends, rather than causative. At Pike River this is difficult to test, because sulphur is usually high only at the top of a seam, declining steadily downwards. Furthermore, most fluidity values exceed 50,000 ddm which appears to be the maximum measurable by CRA. Variations above that value must be estimated from the temperature range between softening and resolidification. However, at Webb/Baynes sulphur is usually high towards the floor as well as the roof, separated by a zone of lower values, and changes in the lower part of the seam to a lower volatile matter/relatively unreactive type clearly override any influence sulphur may have on fluidity (Fig. 160). Investigation of such trends is only worthwhile in the case of fresh samples. Figure 161 relates fluidity to sulphur for samples within the envelope inferred to represent unweathered coals on Fig. 158, and demonstrates the lack of any consistent relationship.

4.6.5 Conclusion

Systematic treatment and comparison of Webb/Baynes lithological, coal petrological, and analytical information has elucidated important relationships between paleoenvironments of peat accumulation and resultant coal properties. Variations in the appearance and abundance of coal macerals, coupled with information on coal thickness and the facies characteristics of overlying strata, suggest that a raised swamp was developed in the Webb/Baynes area with the highest sections of the swamp in the west. Relatively well drained western areas gave way eastward to wetter swamps adjacent to a water body which gradually expanded across the region, drowning substantial areas of peat and raising the water table elsewhere. This depositional history resulted in significant lateral and vertical variability in coal characteristics, including some properties frequently assumed to be independent of coal type. Volatile matter yield, vitrinite reflectance, and fluidity appear particularly sensitive to variations in original peat oxygenation as governed by swamp drainage, and an attempt has been made to separate the relative effects of coal type, rank and weathering on fluidity, an important coal quality variable. Lateral and vertical variations

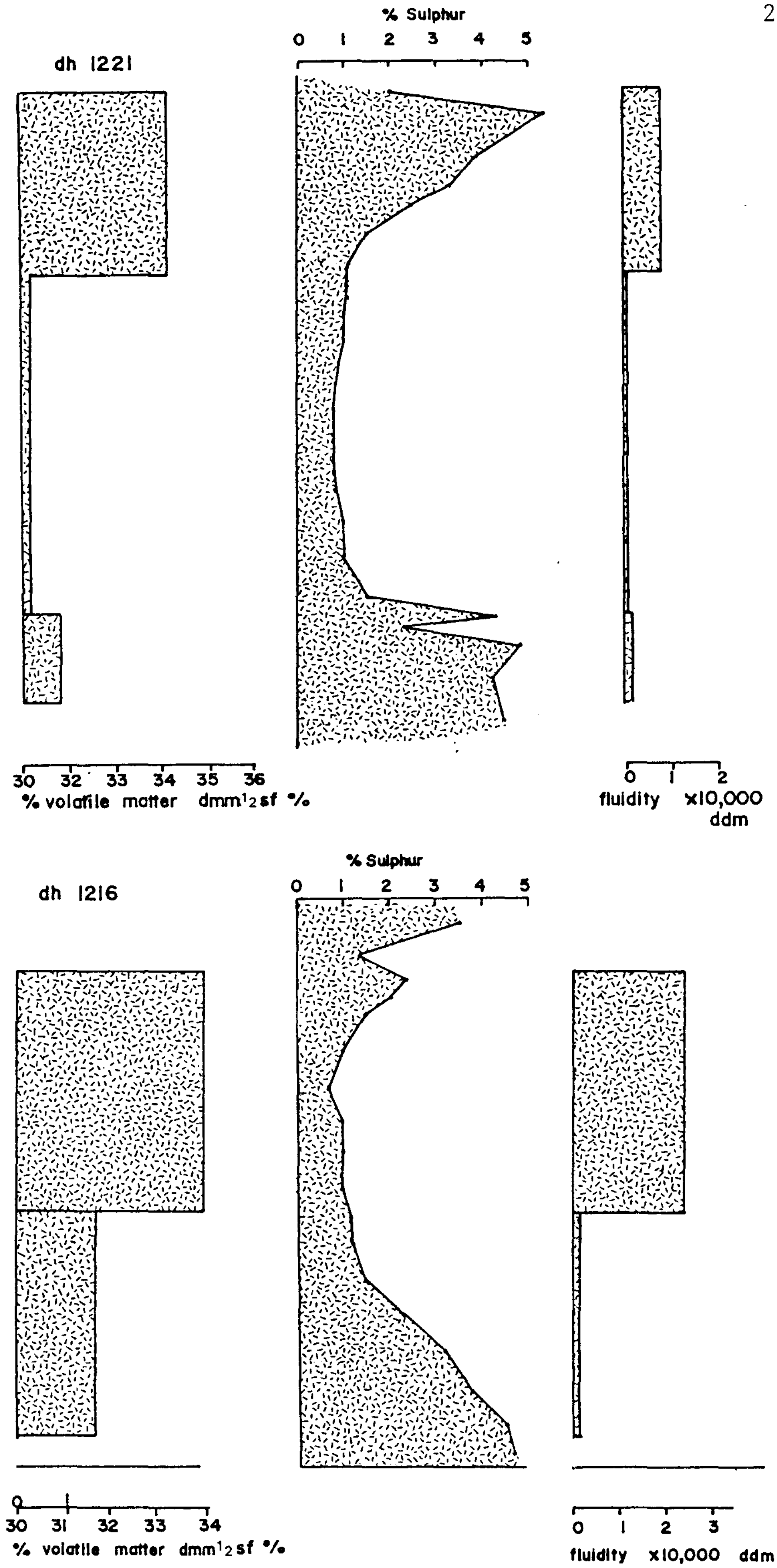


FIGURE 160. Examples of sulphur (dry ash free), maximum fluidity, and volatile matter (dmm½sf, Appendix 8) variations within Brunner seam profiles, Webb/Baynes Block. Whereas there is a good direct relationship between fluidity and volatile matter in unweathered samples, there is no consistent relationship between fluidity and sulphur.

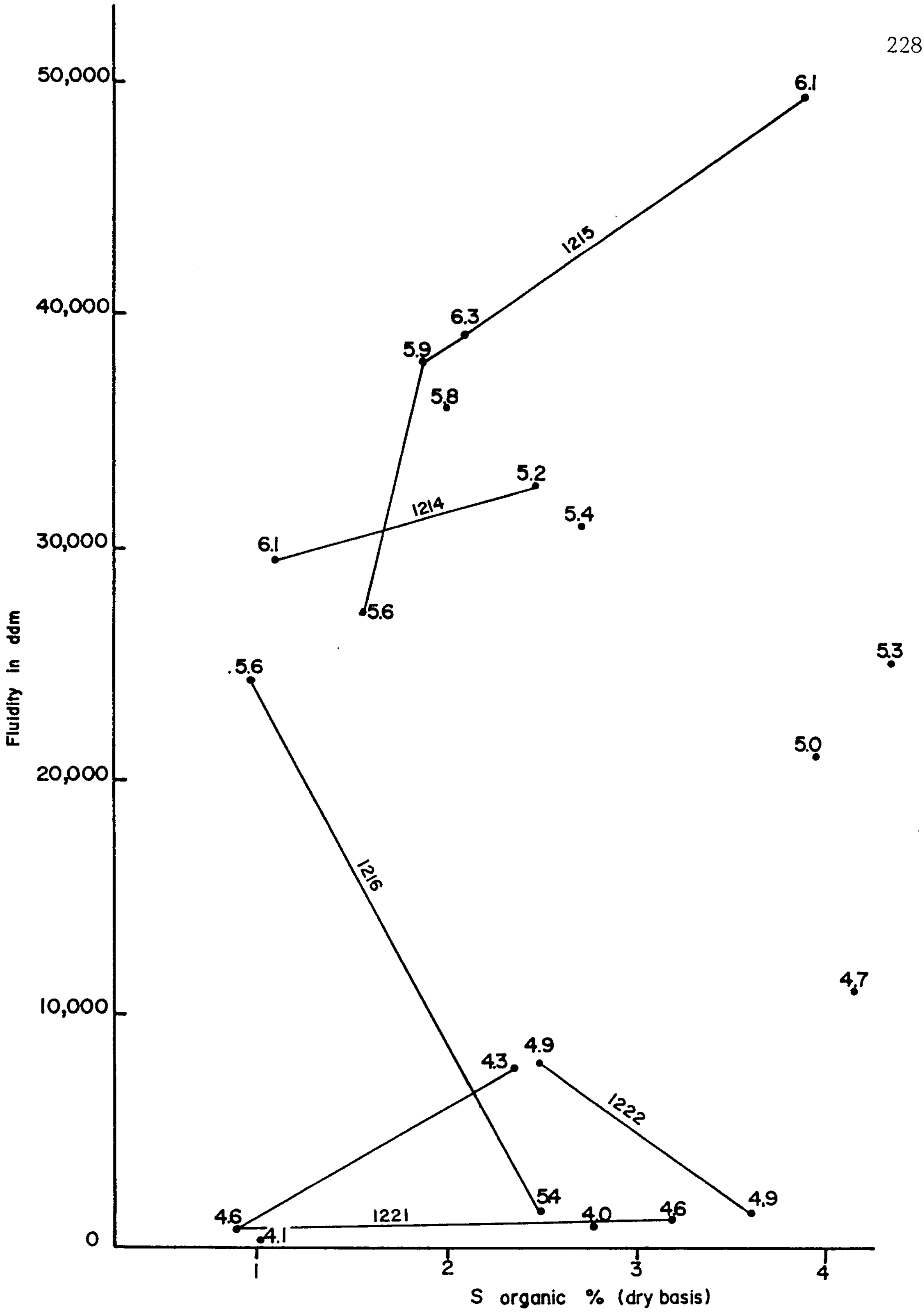


FIGURE 161. Plot of maximum fluidity against theoretically derived values of organic sulphur (dry basis) for unweathered Brunner samples from Webb/Baynes Block, illustrating a lack of consistent relationship.

$$S_{organic}(db) = S_{db} - \frac{Fe_2O_3}{100} \times A_{db} \times \frac{128}{160} \quad \text{(db = dry basis)}$$

(Formula from N.A. Newman pers. comm.)

in sulphur, an important contaminant, appear to have been controlled principally by roof and floor rock permeability rather than by any syndepositional marine influence.

The Webb/Baynes exploration programme has provided exceptional coverage of lithostratigraphic, sedimentological and coal property data, in detail unprecedented in previous West Coast coal exploration. Although the prime motivation of the programme was determination of resource potential for specialist uses, the resulting information provides a valuable basis for more general studies as well. The investigation documented here has sought to take advantage of the unusually complete body of information to confirm and extend fundamental principles established by investigation of other West Coast coals. In this sense the work serves as a case study which should have relevance to other parts of the Buller Coalfield.

4.7 CONCLUSION

The coals and coal measures discussed in Chapter 4 are interpreted, on the grounds of lithostratigraphy and coal type, to have accumulated in depositional environments ranging from non marine high and low moors to marginal marine swamps. Maceral characteristics are correspondingly variable. Despite disparity in depositional setting and properties of coals from Greymouth, Pike River and Buller Coalfields, a fundamental relationship between coal characteristics and inferred peat oxygenation is indicated for all 3 major coalfields. In particular, volatile matter yield, vitrinite reflectance, and fluidity are strongly influenced by variations in vitrinite chemistry related to swamp drainage.

Research documented in Chapter 4 is handicapped in some instances by insufficient or unreliable data. The relationships which have been elucidated are considered sufficiently important to justify more detailed future work on a larger number of coal samples, particularly serial samples, with additional lithostratigraphic investigation to support paleoenvironmental reconstructions where appropriate.

CHAPTER 5

IMPLICATIONS OF VARIABILITY IN THE PROPERTIES OF ISORANK VITRINITE

5.1 ASSESSMENT OF COAL RANK

5.1.1 Introduction

Coal geologists and technologists and petroleum geologists have a common need to describe coal in terms of relative rank. *Rank* is a general term usually signifying degree of chemical coalification achieved as a result of geothermal influence, or in modern idiom, degree of *thermal maturity*. In this thesis, coals of equivalent rank are simply regarded as those that have been subject to the same burial history, as in the case of serial samples taken from a common seam intersection. It is not considered necessary within the scope of this thesis to elaborate further on rank theory.

In practise, rank is easier to define than to measure. Coal rank has traditionally been estimated on the basis of moisture content in the case of coals up to bituminous rank, and thereafter by volatile matter yield. Calorific value is also relevant to rank assessment. There are many problems associated with these methods, including the difficulty of measuring bed moisture accurately, as required by ASTM (American Society for the Testing of Materials), and of standardising conditions for measurement of 'air-dried' moisture content which is generally used in preference to bed moisture in New Zealand. For example, ACIRL (Australia) values for air-dried moisture in low-ash, high-volatile bituminous C Greymouth coals are consistently lower than CRA (New Zealand) values for the same samples, by up to 50%. Moisture, volatile matter yield and calorific value all require correction for mineral matter content and composition before values for different samples can be compared, and in the case of volatile matter and calorific value a correction for organic sulphur is also required. In general, these problems have not been adequately overcome, although advances are now being made (N. A. Newman, in press).

In addition to difficulties entailed in measurement and correction of coal properties, there remains the complicating influence of coal type, which, as a consequence of the influence of swamp conditions on peat and hence eventual coal chemistry, affects all the properties mentioned above and cannot reliably be allowed for. Suggate (1959) recognised the difficulty and proposed a method for correcting coals to an average type basis, whereby type numbers are allocated and used in rank comparisons. Problems envisaged in the use of this technique are discussed in Section 5.1.4.

In view of the difficulties entailed in rank assessment by traditional methods, vitrinite reflectance became popular when promoted as an easily measured property which varied linearly with changes in coal rank, and was independent of mineral matter, sulphur and, apparently, coal type effects. The technique was particularly attractive to the petroleum industry, because it can be applied to tiny fragments of carbonaceous material (phytoclasts) separated from both marine and non-marine sediments, permitting construction of a continuous rank profile for prospecting wells. There is now considerable basis for doubt regarding the reliability of vitrinite reflectance as a rank indicator for certain coals, however fundamental problems associated with the method appear to have received little attention except in New Zealand (Suggate & Lowery 1982, Newman J. and Newman N.A. 1982). Contributions of this thesis to assessment of the significance of vitrinite reflectance in New Zealand coals are summarised in the following section.

5.1.2 Vitrinite reflectance as a rank indicator

The widespread use of vitrinite reflectance as a rank indicator rests on the assumption that reflectance is independent of all other variables, particularly coal type. There appears to have been little critical assessment of this fundamental assumption. Brown et al. (1964) noted that 'vitrinite A' (broadly equivalent to telocollinite) tends to have a significantly higher reflectance than 'vitrinite B' (principally desmocollinite) in any particular sample, and attributed this to chemical differences, demonstrating a higher volatile matter yield and hydrogen content for vitrinite B than vitrinite A in the Australian and European coals they studied. They implied that this complication could be overcome by limiting reflectance measurements to vitrinite

A, or in practise, to telocollinite, as has been done in the present study. There is no suggestion in their paper that vitrinite A might vary, in chemistry and hence vitrinite reflectance, between different samples of equal rank.

As discussed in Section 4.3, my initial work on coals and coal measures at Pike River Coalfield suggested that vitrinite reflectance is strongly influenced by original peat oxygenation, as controlled by the effect of swamp drainage on water levels. Relatively alkaline conditions resulting from marine influence are proposed as a secondary control on peat character. Both coal petrography and lithostratigraphic data are presented in support of these interpretations, which have been confirmed by subsequent work (see 4.3 to 4.6). The fundamental theory for the oxygen/pH hypotheses is presented by Stach et al.(1982) and Teichmuller (1974), but appears to be regarded by these European coal scientists as a peculiarity limited to few coals, and therefore not a significant obstacle to the use of vitrinite reflectance for rank assessment. In contrast, the writer's work on Paparoa and Brunner coals from 3 West Coast coalfields (see 4.2 to 4.6) indicates that the phenomenon is very common in the case of New Zealand's bituminous coals, and that indiscriminate use of vitrinite reflectance as an indication of coal rank should be avoided.

The widespread adoption of vitrinite reflectance as a reliable index of coal rank in bituminous coals suggests that many overseas coals exhibit little isorank variation in the reflectance of telocollinite. However, overseas coals must, in many cases, have accumulated in very wet and relatively anaerobic swamps, similar to those which produced perhydrous Paparoa and Brunner coals with depressed reflectance. This apparent inconsistency is attributed to the fact that most overseas bituminous coals are Carboniferous or Permian in age, while most Cretaceous-Tertiary coals are of relatively low rank, except for those in the circumpacific region (e.g., New Zealand, Japan, Indonesia). Paleozoic-early Mesozoic peat swamp floras probably differed compositionally from the gymnosperms and angiosperms which formed the younger peats. Research results in this thesis suggest that the younger (New Zealand) flora was capable of generating a relatively broad range of vitrinite compositions in response to variations in swamp conditions. A higher proportion of hydrogen-rich compounds (e.g., cellulose and lipids) in the younger flora would explain an increased tendency, since the Cretaceous, for anoxic peats to produce the perhydrous bituminous coals which are common on the West Coast. It is probable that critical assessment of vitrinite reflectance in other Cretaceous-Tertiary basins which achieve bituminous ranks will show that the reflectance anomalies detected on the West Coast are far from unique.

Although this investigation has focussed on coal, the paleoenvironmental influences discussed may also apply to phytoclastic material deposited in poorly oxygenated environments. Phytoclasts are sometimes used in addition to coal for assessment of basin maturity by vitrinite reflectance in petroleum prospecting. Several large subsurface basins in the New Zealand region are currently subject to petroleum exploration, and reflectance data indicate that extensive areas are submature to mature. In view of the findings documented here for West Coast coals, reflectance data for petroleum wells in Cretaceous-Tertiary strata should be interpreted cautiously.

5.1.3 Alternative methods of assessing basin 'maturity'

Vitrinite reflectance is only one of several methods currently employed to assess the rank or 'maturity' of basins with hydrocarbon potential. Reflectance is favoured because it is relatively quick and easy to determine, however sophisticated tests involving the chemical characteristics of organic matter present in cuttings or core, although more difficult and expensive, are also important. It appears likely that these chemical characterisation techniques will be influenced by type variation. Recent research undertaken jointly by Department of Scientific and Industrial Research (Chemistry Division) and Victoria University staff has used Nuclear Magnetic Resonance (NMR) spectroscopy to characterise coals in terms of molecular structure (Newman, R.H. et al 1984). Certain NMR parameters are believed to indicate coal rank, however application of the technique to selected Webb/Baynes samples provided by the writer resulted in differentiation of the basal ply in Drillhole 1241 (31/112, low volatile matter/high reflectance, see 4.6) from overlying plies (S J Davenport, pers. comm.). The 3 plies comprise serial samples and by definition must be of equal rank, hence type differences are producing an effect similar to that expected from rank variation. In view of the very low exinite (½-1%) and inertinite (½-3%) contents of these samples the bonding characteristics assessed by the technique must relate to vitrinite chemistry.

Another method sometimes used for rank assessment is spore colour and fluorescence. Investigation of Webb/Baynes Brunner, and Pike River Brunner and Paparoa coals, indicates that between samples of equal or similar rank sporinite in polished section varies considerably in reflectance. In general, high volatile-type coals have darker sporinite than low volatile-type examples, and in blue light irradiation the former fluoresce much more strongly than the latter. These observations are consistent with the behaviour of vitrinite reflectance and chemistry with change in type, and although quantitative measurements are not available, suggest that spore characteristics are not a reliable indication of rank.

5.1.4 Suggate rank

The 'Suggate rank' scheme (Suggate 1959) claims to accommodate coal type variability along isorank lines. Coals of equal Suggate rank appear as colinear points on plots of carbon and hydrogen content (dry, mineral matter, sulphur and nitrogen free), and also on plots of volatile matter and calorific value (dmmsf). The principal assumption of Suggate's scheme with respect to New Zealand coals is that the relative proportions of carbon, hydrogen and oxygen in isorank coals conform to a simple linear relationship with variation in type, and concomitantly that coals with similar proportions of these elements are necessarily of similar rank. In view of the variability in chemistry inferred for isorank vitrinites, on the basis of volatile matter and reflectance variability and other properties, Suggate's assumptions appear likely to be invalid. A critical analysis of the Suggate rank scheme has been undertaken jointly by the writer and N. A. Newman (Newman, J. & Newman, N. A. 1982, 1983) and is not reproduced here.

5.1.5 Conclusion

Potentially large variations in the composition and properties of isorank vitrinites, both telocollinite and desmocollinite, have important implications for rank assessment. It is unwise to assume that concepts and techniques developed for Paleozoic coals can be applied directly to Cretaceous-Tertiary coals, and it is also erroneous to assume that all New Zealand coals have, at any particular rank, very similar chemistry and properties. All methods of rank assessment involving coal appear to lack independence of the effects of type variation, and this limitation probably extends to all methods involving organic matter.

5.2 PETROLEUM SOURCE POTENTIAL

Where vitrinite is highly predominant, as in nearly all New Zealand coal measures, variation in vitrinite type must have an influence on petroleum source potential. Chapter 4 presents evidence that vitrinite in many West Coast coals is strongly perhydrous, and this is attributed to relatively anoxic peatification. Perhydrous vitrinites are an important petroleum precursor (e.g., Stach et al 1982 p.67). Conversely, some coals are relatively subhydrous (hydrogen deficient). Basin tectonics are frequently an important factor influencing swamp water levels and hence oxygen availability. Consequently, although petrographic data indicate that both types of coal can occur in close proximity, it appears likely that coal measures may be inherently more perhydrous in some basins or parts of basins, and petroleum generation could vary accordingly.

5.3 ASSESSMENT OF PROPERTIES RELEVANT TO COAL UTILISATION

5.3.1 Introduction

Variability in the chemistry and properties of isorank vitrinite is likely to complicate the assessment of vitrinite rich coals for their application to certain industrial processes. Case studies in Chapter 4 indicate that coal characteristics can vary abruptly both laterally and within a seam profile, implying that adequate resource description and assessment depends on a detailed understanding of the reasons for, and pattern of, variation in important variables. It is beyond the scope of this thesis to discuss a wide range of utilisation technology. The following comments apply to the two end-use industries which are chiefly affected by coal type, i.e., carbonisation and conversion.

5.3.2 Carbonisation

New Zealand's bituminous coals are renowned for their very high swelling and fluidity. Black (1980) states that this exceptional behaviour results from their very high vitrinite content, but vitrinite composition is also important. Perhydrous vitrinites exhibit high swelling and fluidity (Stach et al 1982), and this is demonstrated by Paparoa and Brunner coking coals. In regions which exhibit large variations in vitrinite character, for example Webb/Baynes Block (4.6), variability in carbonisation behaviour unrelated to coal rank or weathering can be expected (Newman, J. 1984).

Vitrinite reflectance is often used as the primary basis for prediction of carbonisation behaviour and coke properties (Zimmerman 1979), and such predictive techniques commonly assume a simple and constant relationship between reflectance and coke characteristics, with little allowance made for type-controlled variability in reflectance. Although these methods appear to be adequate for many overseas coals, they can be expected to produce erroneous results if applied to coking coals which have anomalous vitrinite reflectance.

5.3.3 Conversion to liquid fuels

Possible derivation of liquid fuels from New Zealand coals has attracted considerable interest for several years. High exinite content is commonly regarded as a favourable characteristic in coals considered as a conversion feedstock, however work on West Coast coals (Chapter 4) strongly suggests that hydrogen content and volatile matter yield frequently exhibit little variation with exinite content, but show a marked dependence on vitrinite character. Research presented in this thesis is limited to coals of bituminous rank, whereas lower rank reserves are usually favoured for conversion processes. However, type-related variability in vitrinite characteristics originates at the peat stage and can be expected to influence the properties of lignites and sub-bituminous coals as well as those of higher rank.

5.4 PALEOENVIRONMENTAL STUDIES

Although vitrinite reflectance is conventionally used for rank assessment, relationships between reflectance, coal analyses, and inferred paleoenvironments of serial samples, as discussed in Chapter 4, indicate that vitrinite reflectance - in conjunction with volatile matter yield - has considerable application to paleo-environmental interpretation. Given constant or similar rank, vitrinite reflectance varies directly with inferred oxygenation during peatification, and independent paleoenvironmental evidence in the form of maceral characteristics and associations and litho-stratigraphic data has accrued in support of this interpretation. Regional variations in reflectance at a known horizon can contribute to paleogeographic reconstruction. In addition, where a seam is examined in several plies, vertical variations in reflectance in association with other properties provide a history of swamp conditions at that site which can often be related to regional paleoenvironmental evolution. Although vitrinite reflectance has been demonstrated in this thesis as a paleoenvironmental indicator in West Coast coalfields only, reconnaissance work by the writer on sub-bituminous coals elsewhere in New Zealand strongly suggests that the principles established on the West Coast have general application to Cretaceous and Tertiary coals in New Zealand.

ACKNOWLEDGMENTS

This research was funded initially by University Grants Committee and BP New Zealand Ltd Postgraduate Scholarships, and subsequently by the New Zealand Energy Research & Development Committee, who also funded the purchase of a petrographic microscope (part), camera, and equipment for the preparation of petrographic mounts. Valuable cooperation and assistance was provided by administrative and district staff of New Zealand Mines Division, State Coal Mines, New Zealand Geological Survey, and Lime & Marble Ltd. The practical advice and assistance provided by Mr Frank Taylor and associates at the Dunollie office of State Coal Mines warrants special mention in connection with the early stages of research. Study of important coal measures at Pike River Coalfield was made possible by Mr T. E. Bates of Pike River Coal Company, who has generously authorised use of certain field and analytical data.

Professor A. C. Cook of the Wollongong University Geology Department provided tuition and access to coal petrology facilities at the commencement of research, and Professor P. M. Black of the Auckland University Geology Department made available on numerous occasions equipment for ongoing vitrinite reflectance measurement and fluorescence studies.

Drs D. W. Lewis and J. D. Bradshaw of the University of Canterbury Geology Department kindly read the manuscript and made many helpful suggestions. Dr R. P. Suggate of the New Zealand Geological Survey provided useful comment on some interim reports and papers.

Mr Albert Downing willingly prepared photographic plates of the necessary high quality.

I am grateful to my husband, N. A. Newman, who has assisted in field and sampling activities, development of techniques for sample preparation, correction of volatile matter values for the effects of mineral matter, and who has cooperated in frequent discussions of data interpretation.

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APPENDIX 1

LITHOSTRATIGRAPHY OF MORGAN, WAIOMO, AND BASAL REWANUI SEDIMENTS AT 12 MILE BEACH, GREYMOUTH

INTRODUCTION

Paparoa CM are generally well exposed in the shore platform at 12 Mile Beach and in bluffs between 12 Mile Beach and 10 Mile Creek (Fig. 2). These exposures are of particular interest because they are the closest to the original western margin of the basin. Jay and Ford Members are absent. The succession consists predominantly of alluvial fan conglomerates derived from the western margin, and due to the persistence of a fan environment Rewanui and Dunollie Members are not separated by the Goldlight Member, which is believed to be represented in this area by fluvial sediments equivalent in age to lacustrine mudstones occurring further east (Gage 1952).

During the summer of 1978/79 I measured and described in detail a section up to the base of the Rewanui Member, using tape and compass. Stratigraphic columns were initially prepared at a scale of 1cm=0.5m and have been simplified for inclusion in this appendix (Fig. 162).

MORGAN MEMBER

Morgan conglomerates rest on slightly weathered Greenland Group basement at a well exposed angular unconformity on the wave cut platform. Most of the sequence dips very shallowly and beds thicker than c.0.5m are consequently exposed for several metres perpendicular to strike. Due to the width of the platform some beds can be traced for 100 to 200m along strike. Coarse units undergo abrupt pinching and swelling, and lateral changes in texture sometimes occur over distances of a few metres where conglomerate interfingers with sandstone within channelised units.

The lower 20m of Morgan sediments are dominated by clast-supported conglomerate which is generally sorted and often imbricated. Particularly

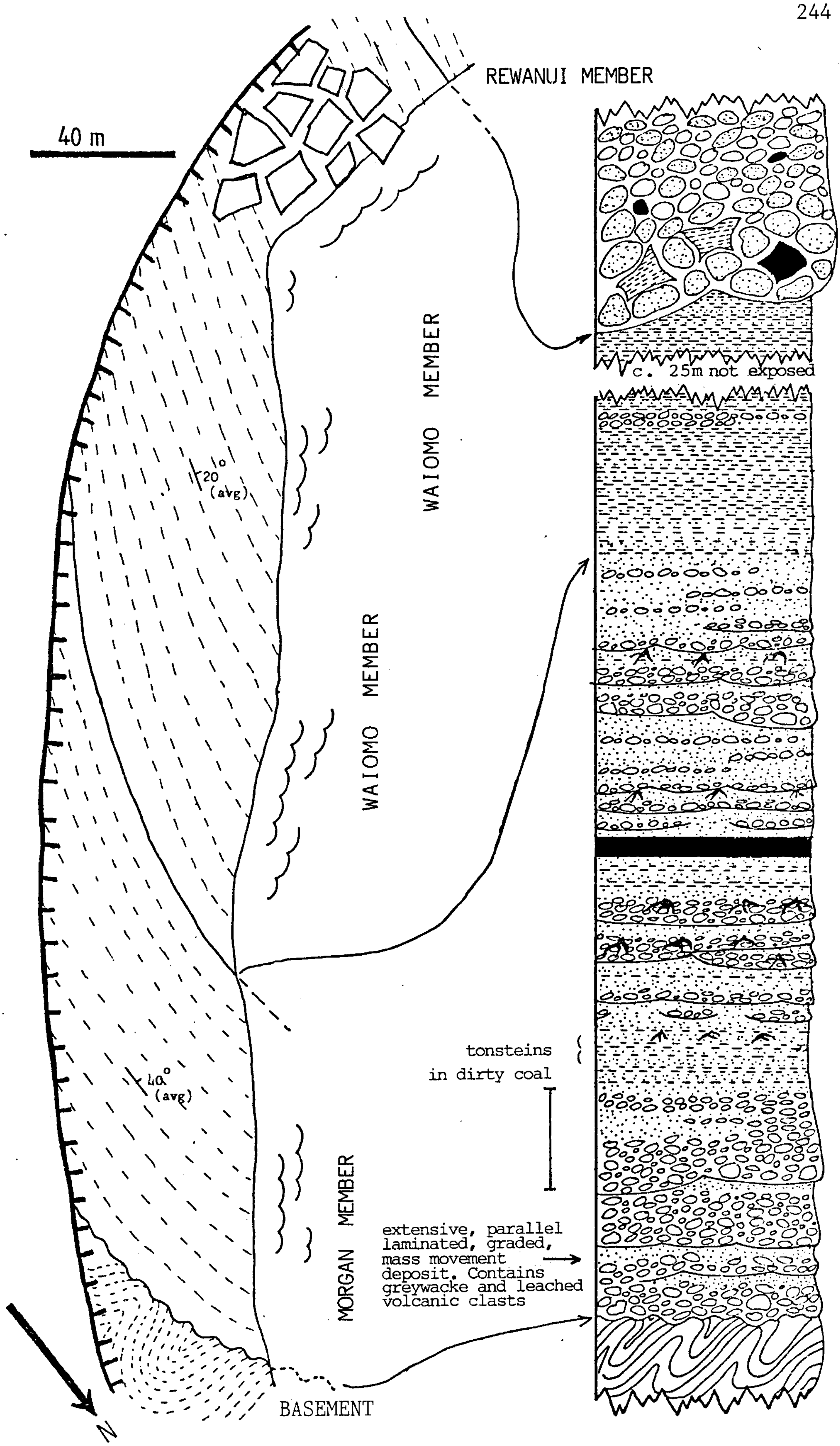


FIGURE 162. Map and column of 12 Mile Beach Section.

large clasts (>0.5m) occur sporadically, usually near the base of otherwise sorted beds. Greywacke pebbles predominate, with minor quartz and hornfels and rare rhyolite. The conglomerates are interbedded with relatively thin lithic sandstones. One such fine but extensive unit consists of strongly parallel laminated, normal and reverse graded, well sorted sand and grit sized lithic clasts. In addition to a distinctive texture and structure this unit has an unusual leached appearance, and is interpreted by the writer to be a mass flow deposit with a volcanic component. Reconnaissance trace element analysis confirms the presence of volcanic material (N. A. Newman, pers. comm.).

Above the lower 20m of the Member sandstones and mudstones predominate, although coarse conglomerates persist. Large, complex root systems occur both within the finer units, where they are sometimes truncated by overlying coarse units, and within the conglomerates, as illustrated in Figure 162. Many of the mudstones are carbonaceous, and a 2m coal seam occurs halfway up the Member. Reconnaissance coal petrography indicates that plant debris was intermixed with mineral matter in a very wet and frequently flooded swamp. Thin coals and carbonaceous mudstones lower in the sequence contain layers of kaolinised volcanic lapilli, or 'tonsteins'.

The Morgan Member at this locality is characteristically disturbed by fluidisation, which has affected sands throughout the Member and even conglomerates near the base. I attribute this phenomenon to rapid sedimentation in association with a high water table. The underlying impervious Greenland Group would have caused water to concentrate in the thin sedimentary cover during floods, resulting in excess pore fluid pressures favouring fluidisation. In addition, volcanic activity, indicated by the volcanic mass flow deposit near the base of the Member, rhyolite pebbles, and tonsteins (Fig. 162), may have been accompanied by earthquakes sufficient to trigger fluidisation.

The abundance of coarse lenticular conglomerate beds in the Morgan Member at 12 Mile Beach, indicating accumulation in a high energy environment, conflicts with preservation of a high proportion of sandstone and mudstone in the succession, and the development of a long-lived peat swamp. In view of these features and a gradational relationship with overlying Waiomo Member lacustrine mudstones, most of the Morgan Member at 12 Mile Beach is inferred by the writer to have accumulated in the lower reaches of an alluvial fan adjacent to a lake margin. The upper c. 50m of the Morgan Member in this area is therefore regarded as facies equivalent to Waiomo Member mudstones further east.

WAIOMO MEMBER

A large proportion of the Waiomo Member on the shore platform is obscured by fallen blocks of basal Rewanui conglomerates. The mudstones which are exposed differ from the Member in most parts of the coalfield in an abundance of coarse silt and sandstone interbeds <1 to 10cm thick, which occur every metre or less and are attributed to flood events. Occasional horizons are conglomeratic, and tiny animal burrows are common especially in sandstone beds. Thin beds of unusual texture and pale colour occurring in the lower 10 to 20m of the Member appear likely to have an ash-fall origin.

In view of the relatively coarse textural characteristics, and the inferred proximity of the western basin margin, the Waiomo Member at 12 Mile Beach appears likely to have accumulated close to the western lake shore.

REWANUI MEMBER

Towards the top of the Waiomo Member sandy beds are relatively thick and coarse and lenses of conglomerate occur. The base of the Rewanui Member is attributed to the first thick bed of conglomerate, however mudstone and sandstone recur above this level and the contact is considered to be gradational. The basal Rewanui conglomerate at 12 Mile Beach is very coarse and includes clasts of coal and mudstone up to 1m across, reworked from underlying members. Part of the deposit is particularly chaotic and clearly results from mass movement. Clast types are the same as occur in the Morgan Member, with the addition of cobbles and boulders of granite which makes its first appearance at this horizon.

The abrupt incursion of very high energy deposits, recycling of older coal measures, and derivation of new granitic source material all indicate upfaulting towards the basin margin. Very large cylindrical burrows more than 5cm across occur in basal Rewanui conglomerates and sandstones. These burrows may be the escape structures of lacustrine animals, consistent with rapid accumulation of coarse basal Rewanui sediments during high energy events.

The remainder of the sequence in this area consists of monotonous conglomerates with minor sandstone, which I have not studied.

APPENDIX 2

LITHOSTRATIGRAPHY OF THE DUNOLLIE MEMBER IN THE SOUTHWEST OF GREYMOUTH COALFIELD

INTRODUCTION

Although the Dunollie Member is thick, extensive, and frequently carbonaceous, workable coal is present only at the top of the member, in a limited area around Dunollie township (Fig. 2). The coal is low in ash, and sometimes also low in volatile matter yield compared with Brunner coals, and other Paparoa coals of similar rank (Wellman, in Gage 1952).

LITHOSTRATIGRAPHY

Dunollie sediments are well exposed in Spring Creek Road (Fig. 2) and a detailed section has been described near the northern limit of seam development. This section is available on file in the Geology Department. The sequence is dominated by a thin-bedded association of siltstones, mudstones, and thin coals, with interspersed relatively thick-bedded medium to coarse sandstones. In general, siltstone and mudstone beds are laterally persistent and tabular, whereas sandstone beds are strongly lenticular. The entire sequence contains abundant fossilised roots from a few centimetres to more than 1m long, often very densely packed; only the lower parts of some thick-bedded (channel) sandstones are not penetrated by roots. Sparse very thick sandstone beds contain truncated root horizons, indicating amalgamation of discrete sedimentation units. Many coalified logs occur within channel sands and lying on carbonaceous horizons; a few still stand upright. This sequence is inferred to have accumulated on a flood-plain which was heavily vegetated and crossed by few active channels. Sheet flooding periodically deposited extensive thin beds of mud and silt; thick vegetation subsequently grew in these overbank fines and in emergent channel sands. Between floods the fine cohesive mudstones and prolific vegetation acted to confine channels, and many sandstones occur as slender shoestrings completely enveloped in overbank fines. A few of the thicker, more extensive sands probably reflect channel migration, but no evidence of lateral accretion has been found.

Recent drilling has demonstrated that the thickness and litho-stratigraphy of the Dunollie Member is complex in the Runanga-Dunollie area. Abrupt thickening south of Seven Mile Creek indicates marked differential subsidence, in an area which was previously stable as shown by isopachs for earlier Paparoa Members (Figs 14, 15 & 16). A thick intrusive body of diorite in Goldlight sediments of Drillholes 654 and 655 nearby (Fig. 12) may represent the same phase of tectonic activity that caused upper Dunollie differential subsidence. In this regard, it is interesting that prominent sandstones beneath the uppermost Dunollie coal seam at Spring Creek Road (Fig. 2) contain a distinctive mineral assemblage, including fresh feldspar, abundant biotite and chlorite, and other mafic minerals. This assemblage could be of volcanic origin, related to diorite intrusion.

DISCUSSION

A general absence of coal in the Dunollie Member, despite the relative abundance of fine sediments compared with underlying members which are coal-bearing, parallels the circumstances of Paparoa Member 5 at Pike River Coalfield. In both cases, a diminished rate of subsidence, associated with frequent flooding, is considered likely to have limited the thickness of peat deposits. Warmer temperatures (and possibly drier conditions) may also have been a contributing factor, accelerating the rate of decay. The latter hypothesis is consistent with the relatively low volatile matter yield of Dunollie coals. The presence of workable coal only in the Dunollie area may result from (i) the same limitation of fluvial activity that produced thick (and sometimes relatively low-volatile) upper Rewanui coal in this area (see 4.4), and/or (ii) proximity to a lacustrine environment. A thick (90m+) interval of upper Dunollie mudstones in Drillhole 644, which may correlate with coal-bearing upper Dunollie further east, appears to have accumulated in a consistently low energy, possibly lake-margin environment. Dunollie coals could therefore have accumulated preferentially on the margins of this relatively wet area. Poor development of coal in Drillhole 644 upper Dunollie can be attributed to <u>excessive</u> flooding according to this model.

APPENDIX 3

PALYNOLOGICAL DESCRIPTIONS OF SAMPLES FROM THE BIRCHFIELDS AND SEWELL PEAK SECTIONS, BY J I RAINE (1982)

Raine (1982 pp2-4) provided the following interpretation of samples collected by me for dating.

3. *Sewell Peak Section (K31)*

The coal seam within "Island Sandstone-like" sandstones yielded a fairly well-preserved microflora (K31/f62) with abundant Myricipites harrisii, and also Nothofagus flemingii: Zone D (Ab-Ak). K31/f64 from the base of this facies has a similar (zone D) assemblage although less well preserved. A zone D assemblage was also recovered from K31/f41, collected by S. Nathan from 'immediately below seam exposed on [Sewell Peak] road'.

Despite careful search, Nothofagus flemingii was not found in f65, f66 or f67, although meiospores are reasonably abundant in the first two samples. In all M. harrisii is much less common, conifer pollen and Triorites minor/miniscu1us more abundant. Caryophyllidites polyoratus and Triorites subspinosus are common in f65 and f66. All three samples are Cenozoic, but because of the above factors, and the absence of Cupaneidites or Malvacipollis, which appear at or near the zone B/zone C boundary, I place these localities, from the "Brunner-type" quartz sandstone facies, in zone B(Dt-Dw).

The only sample from the lithic conglomerate facies, K31/f68, was barren.

4. *Birchfield Section (J31)*

I am now happy that all below the Birchfield seam is zone B. I will briefly describe studied samples, starting from the base:

f31: a coniferous assemblage, with Clavifera rudis (Mh-Dt) and Pereginisporis sp. (known previously only from J31/f9775 - Dunollie Mbr. @ 7 chains from railway line up small creek 24 chns west of Moody Creek).

f30, f29: poorly preserved assemblages, with abundant Triorites minor and coniferous pollen. C. rudis in f30, Caryophyllidites polyoratus notable in both, but no Triorites subspinosus seen.

f28: similar to samples below, but slightly better preservation. T. subspinosus present (first appearance Dt).

f27: similar to samples below. T. subspinosus and C. rudis both present.

f26: similar to samples below. Phyllocladidites mawsonii very abundant, T. subspinosus common. Tricolpites phillipsii (first appearance Dt) present.

f23: similar to samples below. Tricolpites secarius (first appearance Dt), T. subspinosus and C. rudis present.

f21: yielded only cuticular remains.

f18: again an assemblage dominated by Triorites minor and coniferous pollen, with no additional taxa noted.

Assemblages from the seam itself are more puzzling:

f36 (basal): a more diverse assemblage than f18, but this may be because of better preservation, allowing more difficult taxa to be identified. Proteacidites annularis, P. cf. adenanthoides, P. crassus, P. asperatus, Dicotetradites clavatus, Myrtaceidites parvus, Myricipites harrisii, Tetracolporites oamaruensis, Malvacipollis subtilis, Triorites canacomyricoides, inter alia, make their first appearances in this section. Triorites minor (+ T. miniscułus, closely related) is still common, as is coniferous pollen, especially Phyllocladidites mawsonii. The low frequency of M. harrisii, and relatively high frequencies of conifers and T. minor, imply 'zone B' but M. subtilis and the variety of proteaceous pollen suggest a transition to zone C.

f35 (1 m above base of seam): very little identifiable.

f34 (3.5m above base of seam, 0.5m below top): poor preservation, but a countable assemblage, in which P. mawsonii dominates (66%). M. harrisii is only 2%, but T. minor not recorded. This assemblage appears to be a conifer-rich type of 'zone C', or maybe late 'zone B'.

f33 (top of seam): M. harrisii now dominates, at 30%. P. mawsonii is still important (19%), as well as a variety of Proteaceae, including Proteacidites spiniferus, not previously recorded below Bortonian strata. This assemblage lacks Nothofagus and is very similar to those classed as 'zone C' elsewhere (e.g. in Arahura-1 @ 5060 ft and 4980 ft).

To summarise, the seam appears to have a transition from 'late zone B' to 'zone C' assemblages. What this means in terms of time I do not know - the details of coal petrography within the seam might be interesting in this regard, in identifying the possibility of hiatuses *by discontinuous change, or conversely suggesting continuity by gradual transition between coal lithologies. Above the seam proper, within 'Island Sandstone' facies, one sample was studied from a thin coal and carbonaceous mudstone bed about 2m stratigraphically above the top of the main Birchfield seam -*

f1: a rich assemblage, notably better preserved than those lower in the section. The rank as judged by spore colour may be slightly lower than in the underlying seam; this is a subtle character, and requires support from, e.g. reflectance studies to be deemed significant. Rare dinoflagellates (Wetzeliella (Rhombodinium) cf. glabra granulata) indicate access of marine water, perhaps tidally, to the site of deposition.

M. harrisii is abundant, and Nothofagus spp., including N. flemingii, appear for the first time in this section. The assemblage is confidently assigned to 'zone D'.

APPENDIX 4

STRATIGRAPHIC REINTERPRETATION OF GREYMOUTH DRILLHOLE-LOGS

Lithological logs of Greymouth drillholes used for isopach data in this thesis are documented in Gage (1952, Drillholes 1 - 269) and on file at N.Z. Geological Survey (Drillholes < c. No. 600) and Mines Division (Drillholes > c.No. 600). All logs include stratigraphic subdivisions, which are adopted in this thesis except in the cases which follow.

Drillhole	
266	Waiomo and Morgan are inferred to be basal Rewanui.
273	" " " " " " " " "
621	47m of basal Rewanui are considered to be Waiomo and 10-15m are removed from the Rewanui to allow for steep dips.
631	Basal tuffaceous interval is attributed to the Waiomo instead of the Morgan.
633	50m of basal Dunollie sediments are considered to be Goldlight.
634	31m of basal Rewanui are attributed to the Waiomo.
635	30m of Rewanui are attributed to the Waiomo.
637	"Jay" conglomerates at the base of this hole are attributed to the Rewanui.
639	51m of Rewanui are attributed to the Waiomo.
644	11m of Goldlight are attributed to the Dunollie.
645	80m of Rewanui are attributed to the Goldlight.
	25m of Rewanui are attributed to the Waiomo.
649	29m of Dunollie are attributed to the Goldlight.
654	5m of Waiomo and 36m of Morgan are attributed to the Rewanui.
	75m of Goldlight are attributed to the Dunollie.
656	56m of Rewanui are attributed to the Waiomo.

APPENDIX 5

SANDSTONE THIN SECTIONS AND COAL POLISHED SECTIONS; SAMPLE SITES AND OTHER INFORMATION

THIN SECTIONS

Rapahoe Sector

During work on the Rapahoe Sector at Greymouth a reconnaissance examination of sandstone petrography was undertaken in an attempt to clarify the paleogeography of both southern and northern parts of the Sector. The results of this work were inconclusive (4.4). Laboratory expenses for section preparation were met by Lime & Marble Ltd., who now hold the thin sections. Sample numbers, sites, and estimated compositions appear in Table 10.

Brunner area, Greymouth

As discussed in Section 3.2.2(b), the quartzofeldspathic composition of sandstones previously logged as Morgan Member in Drillhole 273 south of Sewell Peak, is considered to indicate that the sediments are in fact Rewanui Member. The distinction between quartz-(greywacke) lithic and quartzofeldspathic lithologies is clear in hand specimen in the case of medium to coarse sandstones. One medium sandstone thin section which exhibits a significant alkali feldspar element was prepared. This is sample N44 (UC10444) from 2270 feet in Drillhole 273 (Gage 1952), near Brunner.

Pike River Coalfield

A few thin sections were prepared to determine whether glauconite occurs in the Brunner Coal Measures at Patterson's Section in the far south of Pike River Coalfield, and a positive identification was made in sample PS2 (UC10445), a flaggy, carbonaceous fine sandstone occurring beneath the lower coal seam (see 'G', Fig. 48).

Coal samples

All coal samples cited in this thesis are splits of Coal Research Association samples and have CRA file numbers. Sample locations are clearly defined in Tables 1,2,3,6,7 & 8. All cited samples constitute a collection filed with the Geology Department under UC10446.

SECTION NUMBER	SAMPLE SITE	LITHOLOGY	ESTIMATED COMPOSITION
L&M58	between 2 & 6m above C seam in McPhees Section Strongman Mine	fine sandstone	litharenite, greywacke-derived, lithics c. 25-30%; sparse fresh, angular alkali feldspar
L&M59	as for 58	" "	litharenite, greywacke-derived, lithics c. 30%; very sparse fresh, angular, alkali feldspar
L&M60	5 to 8m above C seam in the stone drive between C & D seams, Strongman Mine	fine sandstone	litharenite, greywacke-derived, lithics c. 30%; occasional fresh, angular, alkali feldspar
L&M61	113m in Drillhole 613	very fine sandstone	litharenite (with extensive carbonate replacement), greywacke-derived, occasional fresh, angular, alkali feldspar
L&M62	130.5m in Drillhole 612	fine sandstone	litharenite, greywacke-derived, lithics c. 40%; occasional fresh, angular, alkali feldspar
L&M63	139m in Drillhole 611	very fine sandstone	litharenite, greywacke-derived, lithics c. 40%; sparse fresh, angular, alkali feldspar
L&M64	213m in Drillhole 615	very fine sandstone	litharenite, greywacke-derived, lithics c. 30%; sparse fresh, angular, alkali feldspar
L&M65	564.6m in Drillhole 653	fine sandstone	quartzarenite, with sparse weathered (greywacke) lithic grains
L&M66	266.5m in Drillhole 650	fine sandstone	litharenite, greywacke-derived, lithics c. 50%; no feldspar observed
L&M67	320m in Drillhole 648	fine sandstone	litharenite, greywacke-derived, lithics c. 50%; trace fresh, angular, alkali feldspar
L&M68	480m in Drillhole 644	fine sandstone	litharenite, greywacke-derived, lithics c. 50%; no feldspar observed
L&M69	357.5m in Drillhole 646	fine sandstone	litharenite, greywacke-derived, lithics c. 50%; no feldspar observed
L&M70	324.5m in Drillhole 636	medium sandstone	litharenite, greywacke derived, lithics c. 50%; no feldspar observed
L&M71	301m in Drillhole 642	fine sandstone	litharenite, greywacke-derived, lithics c. 30-40%; no feldspar observed

TABLE 10. Rapahoe Sector thin sections held by Lime & Marble Ltd.

APPENDIX 6

FAULT REPETITION OF BRUNNER SEAM, DRILLHOLE 3, PIKE RIVER COALFIELD

Drillhole 3 intersected two thick seams at the Brunner horizon, separated by a thin quartzose conglomerate and grit (Fig. 163). Comparison of density profiles (Fig. 164) indicates that the upper seam is a fault repetition, and that the top of the lower seam may have been displaced out of the section. Some properties of the upper seam, such as thickness, and sulphur and exinite content, (see 4.5), suggest that it has been displaced some distance - possibly as much as 300m - from the west or southwest. Similarities between density logs of the upper seam in Drillhole 3 and the main seam in Drillhole 5 tenuously support this interpretation (Fig. 165).

Vertical trends in the lower seam of Drillhole 3 are rather weak in the case of most coal properties (Fig. 166), and the zone of low reflectance and high volatile matter which usually occurs at the top of the seam is absent. It therefore appears likely that some metres of coal have been lost from the intersection by faulting, and Fig. 167 exhibits a tentative reconstruction of the stratigraphy and interrelationships of upper and lower seams prior to faulting. Lateral variations in properties such as seam thickness, vitrinite reflectance, exinite, and occurrence of a sediment parting above the main seam, support a reconstruction whereby the upper seam in Drillhole 3 originally lay approximately 300m east or southeast of its present location, to which it has moved by reverse faulting.

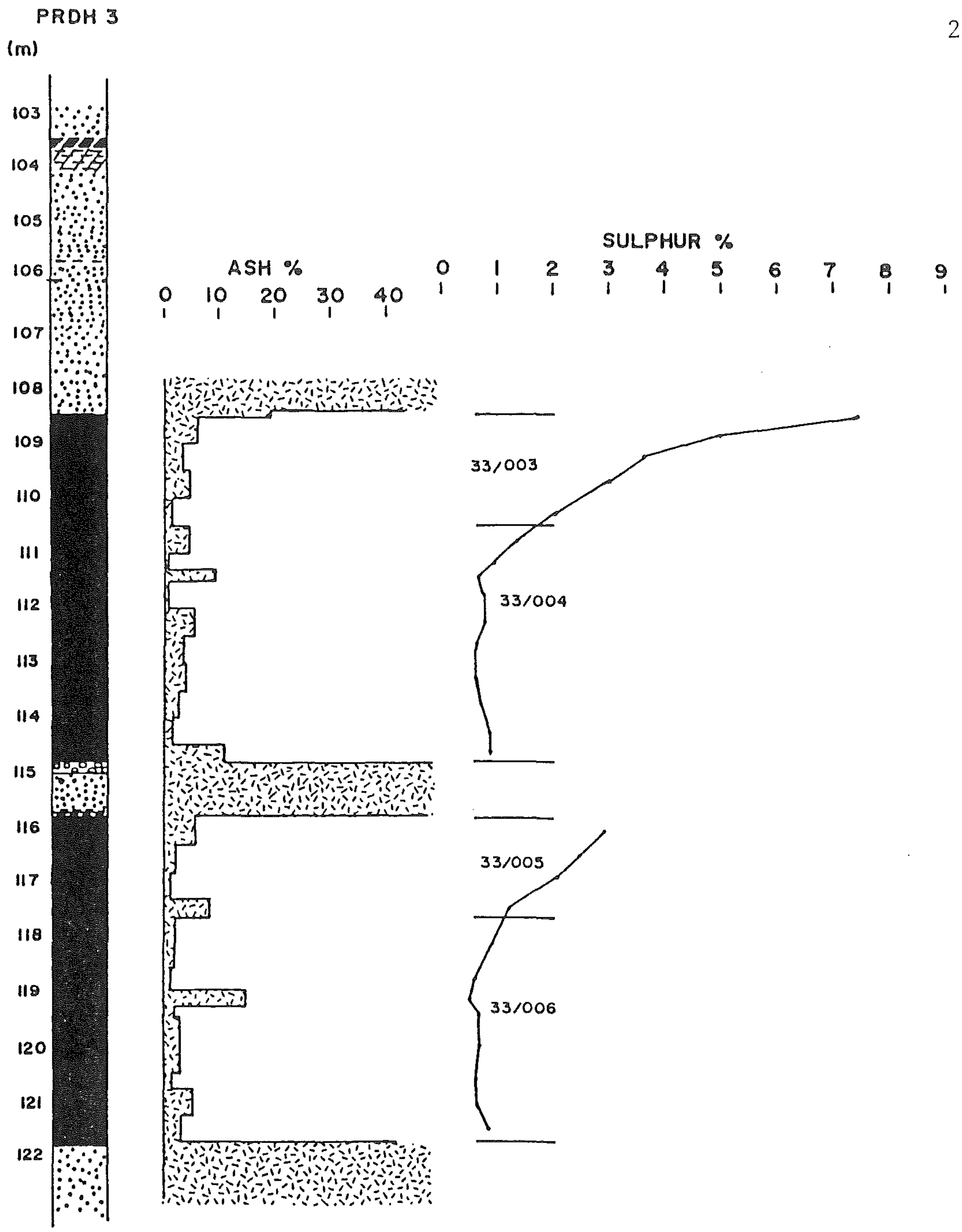


FIGURE 163 Drillhole 3 intersected 2 seams separated by thin quartzose interval.

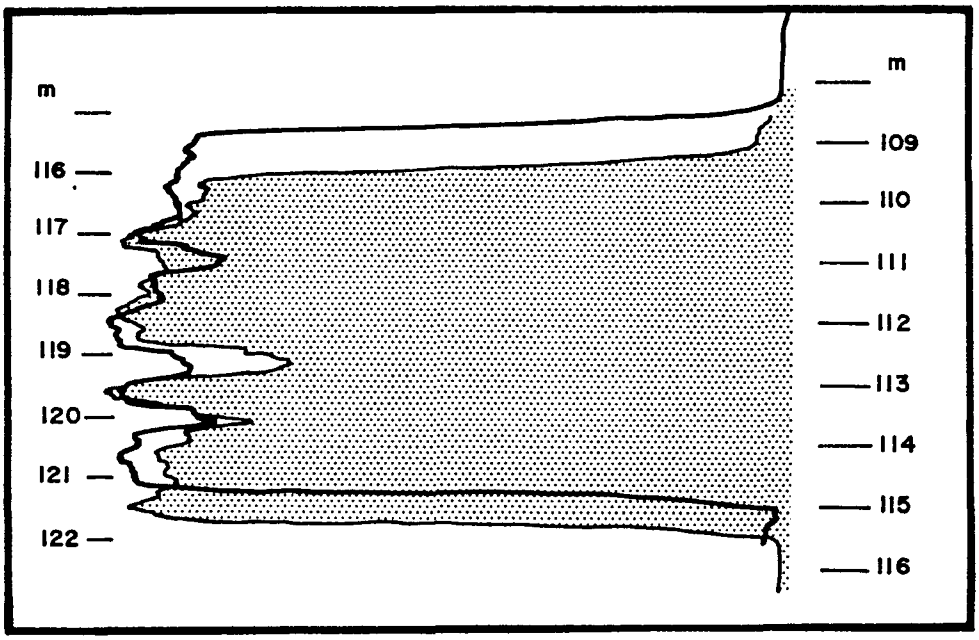


FIGURE 164 Density logs for upper (unshaded) and lower (shaded) seams in drillhole 3, exhibiting significant similarity.

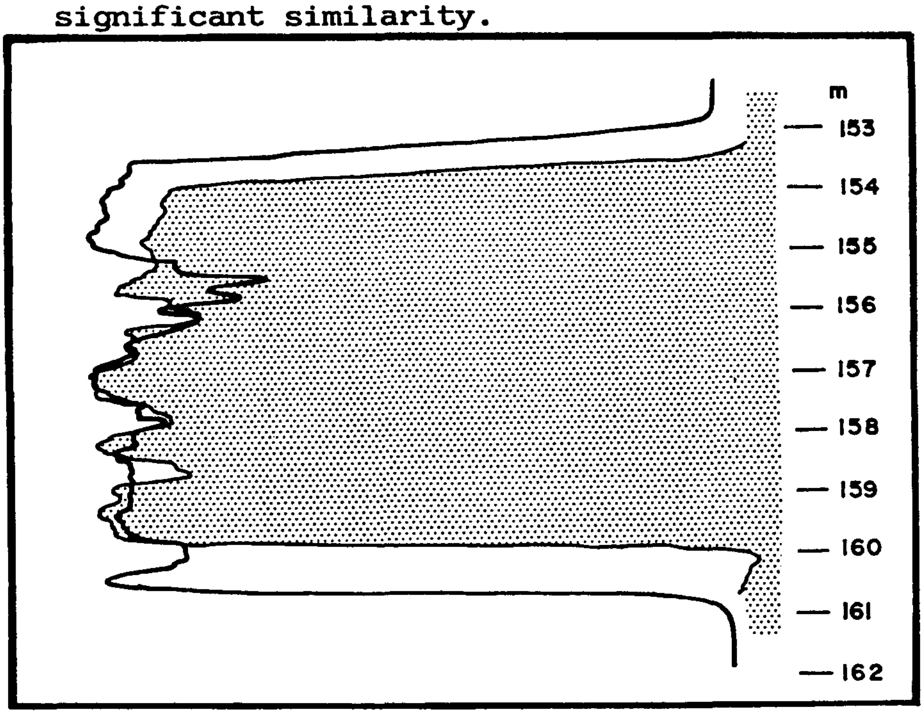


FIGURE 165 Comparison of density logs for upper seam in drillhole 3 (shaded) and main seam in drillhole 5 (unshaded, depth scale on right hand side), exhibiting some similarity.

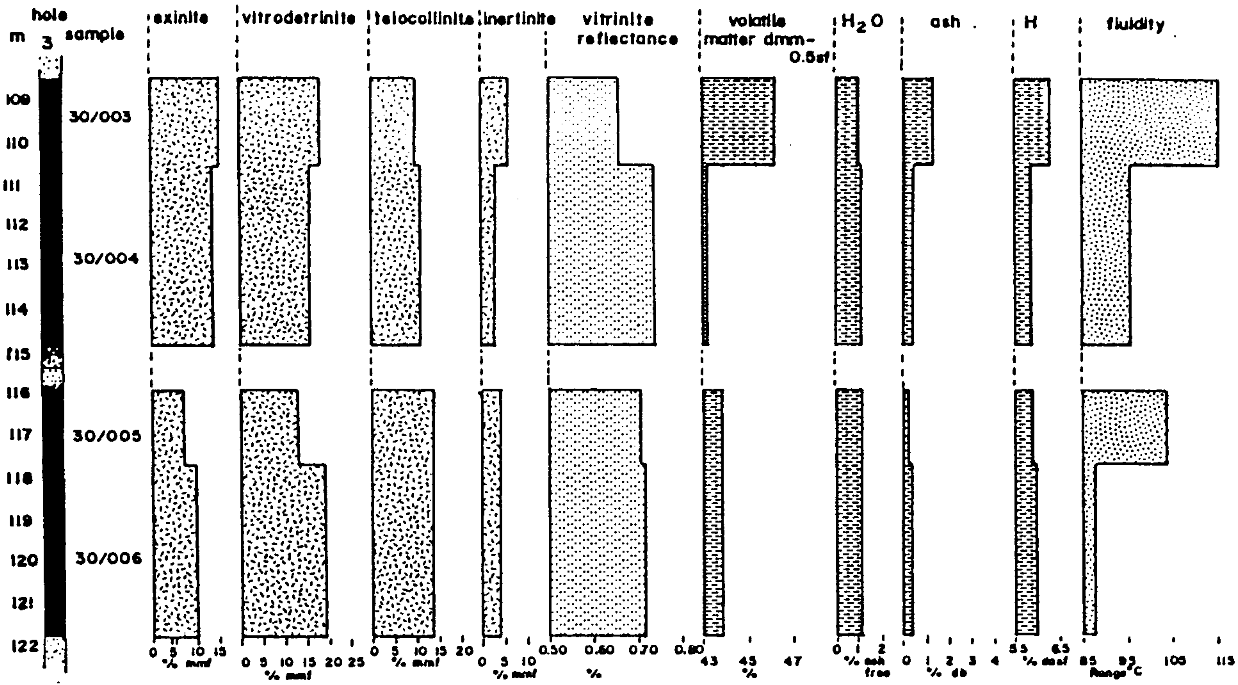


FIGURE 166 Vertical trends in coal properties such as vitrinite reflectance, volatile matter, and ash, are weaker than usual in the lower seam in drillhole 3, suggesting that the upper part of the seam may have been lost by faulting.

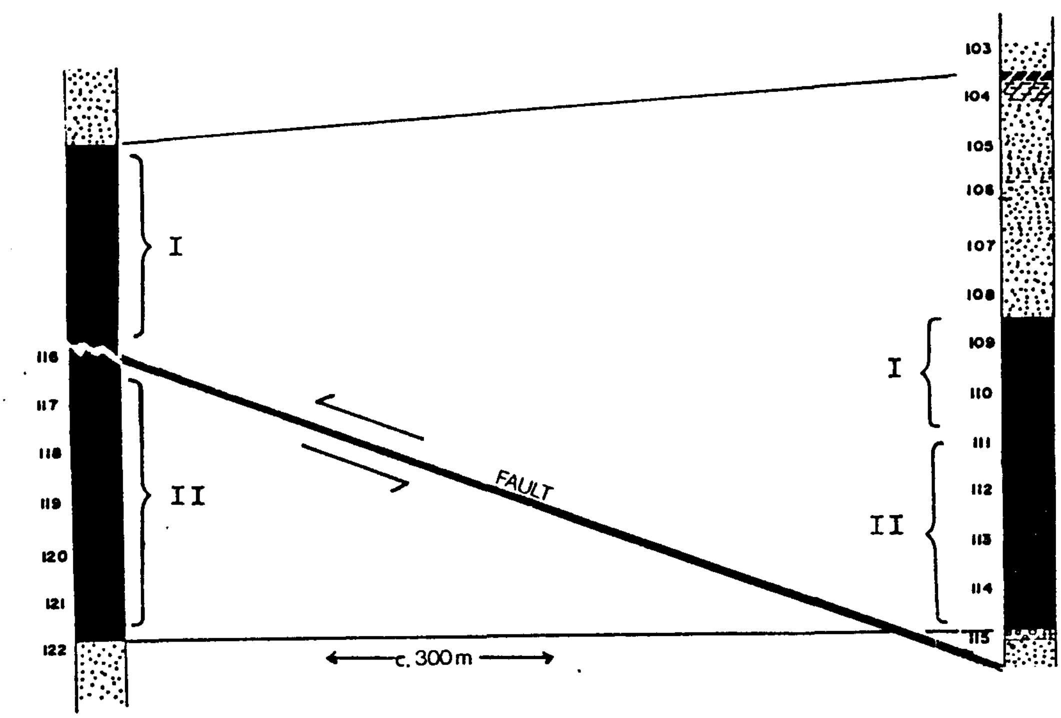


FIGURE 167 Tentative reconstruction of the stratigraphy and interrelationships of upper and lower seams in drillhole 3 prior to faulting, fault plane and sense of movement illustrated. I and II represent type zones; I=$\bar{R}$omax < 0.70%, VM dmm $\frac{1}{2}$sf >45%, II=$\bar{R}$omax >0.70%, VM dmm $\frac{1}{2}$sf <45%.

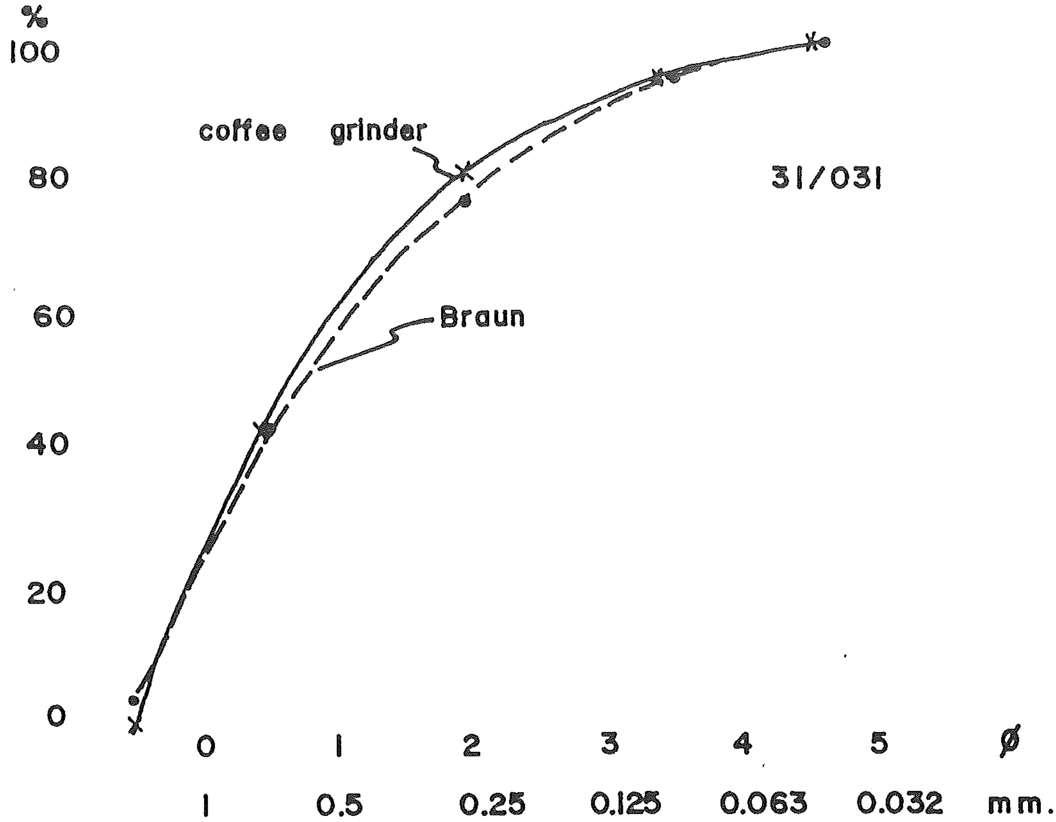
APPENDIX 7

METHODS AND TERMINOLOGY

COAL SAMPLE PREPARATION

Very early petrological work (1978 - 1979) consisted of familiarisation with West Coast coal type, using coal blocks mounted in an epoxy resin. Quantitative maceral analyses and reflectance determinations were not undertaken on these samples. From 1980, studies were restricted to representative splits of exploration programme drillhole and outcrop samples which were supplied by CRA, who also analysed the samples. Material received from CRA consists of 100gm splits ground to approximately -5mm. For some time these samples were reduced to -1mm by hand in a mortar and pestle, but from 1983 a hand operated Spong coffee grinder was employed to decrease processing time. In both cases the coal is ground in several stages, between which the sample is passed over a 1mm sieve so that only over-sized material is reground. Size distribution analysis of test samples indicates that the coffee grinder produces an acceptably low percentage of fines, and the ground product compares favourably with splits of the same samples specially processed, in several stages, for size reduction in the CRA Braun Mill (Fig. 168).

Following repeated splitting to an appropriate sample size, the ground coal is mixed with a two-pot liquid resin in plastic molds and placed in a chamber pumped down to 20 inches (508mm) Hg for up to 15 minutes, in order to extract as many air bubbles as possible. To reduce viscosity, both sample and resin are sometimes heated to approximately 30°C prior to mixing. Excessive heating results in premature setting and sometimes devolatilisation of the resin if the vacuum approaches 24 inches (600mm) Hg. In view of the gravitational separation of particles which can occur prior to setting, the finished mount is examined in a plane which was vertical when the coal/resin slurry was mixed and set. In this way all density fractions should be equally represented during analysis.



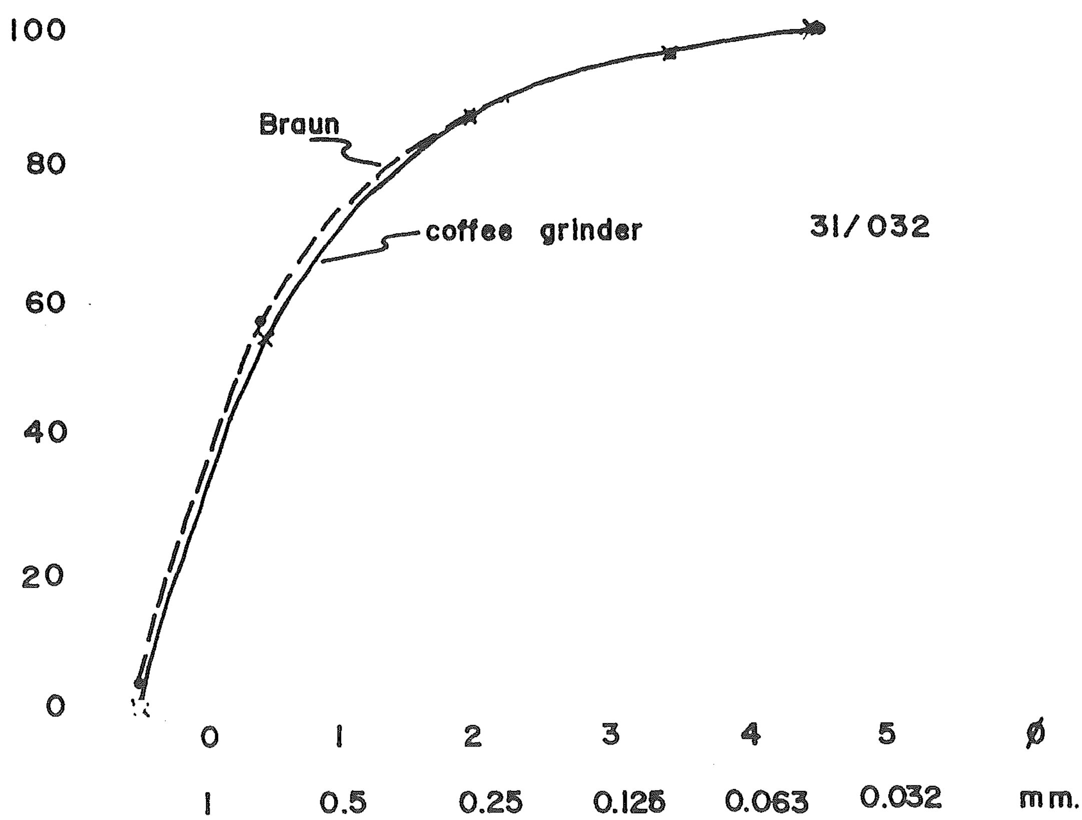


FIGURE 168. Results of grain size distribution analysis of test samples undertaken to determine whether size reduction in a coffee grinder produced an acceptable product for petrographic analysis compared with the CRA Braun mill.

Access to a Buehler heat press was arranged in 1983, but it was found that temperatures in the vicinity of 130°C were necessary to produce a satisfactory mount with conventional thermosetting and thermoplastic materials. Available coal preparation standards (e.g., AS 2061-1977, ISO/DIS 7404/2 Draft) set an upper temperature limit of 100°C for coal intended for reflectance measurements. In addition, West Coast coking coals (e.g., Brunner coal from the Webb/Baynes Block, Buller Coalfield) responded badly to high temperatures and pressures, exhibiting softening and stickiness which adversely affected the quality of the mount and indicated undesirable changes in coal properties. Consequently, the liquid resin technique was retained.

After initial face grinding, the samples were cleaned in an ultrasonic bath and polishing commenced on a rotary lap using Buehler <u>Mastertex</u> cloth with a chrome oxide slurry. After a further ultrasonic wash the samples were finished with careful hand polishing on a stationary lap using Dewmet selvyt cloth with a thick magnesium oxide slurry. This procedure produces a good scratch-free polish with minimal relief in the case of West Coast bituminous coals, many of which are very soft and require particular care for successful polishing.

ANALYTICAL METHOD

Maceral analyses were undertaken using a Leitz Ortholux II, purchased by the Department of Geology in 1980 with assistance from NZERDC Contract 3122. 500 counts were made per sample on a Swift point counter with movable stage adjusted to a suitable sample point spacing. Only one count was made per grain. Until 1982, photographs were taken using a Zeiss Ultraphot, after which a Leitz camera was purchased for the Ortholux, using funds from NZERDC Contract 3122. Except for an early visit to use NZ Geological Survey reflectance equipment, all reflectance determinations have been made with the Leitz Orthoplan MPV2 system which is housed in a temperature controlled room in the Geology Department at Auckland University. The machine is calibrated with reflectance standards covering the range 0.4 to 1.2% . An appropriate Leitz immersion oil (RI 1.5180) was used.

TERMINOLOGY

Terms used for maceral description follow the recommendations of the 1971 edition of the International Committee for Coal Petrology (ICCP) Handbook, and Stach et al. (1982). Occasionally a new term is used to accommodate a particular maceral variety which is important in a certain coal, and such terms are defined as they appear in the text. Reconnaissance investigations indicated at an early stage that the distinction between telinite and telocollinite is rarely useful in the case of West Coast coals, because tissues which can conclusively be said to consist solely of cell wall material are rarely observed. For this reason telinite does not appear in the maceral analyses, although it is identified in some photographs.

APPENDIX 8

CORRECTION OF VOLATILE MATTER VALUES

CONTRIBUTIONS MADE BY MINERAL MATTER AND SULPHUR

The influence of coal type variation on volatile matter yield of West Coast coals has been recognised for some time. Suggate (1959) attempted to develop a mathematical formula to correct volatile matter for contributions made by mineral matter and sulphur, so as to identify variations due specifically to coal type. Suggates 'dry mineral matter and sulphur free' (dmmsf) volatile matter is calculated by the equation:

$$\text{VMdmmsf\%} = \frac{100\ (\text{VMdb} - 0.1\text{Adb} - \text{Sdb})}{100 - 1.1\text{Adb} - \text{Sdb}} \qquad \text{db = dry basis}$$

This correction method makes the following assumptions; (1) all the sulphur is evolved with the volatile matter, and (2) the mineral matter/ash ratio is 1.1. In the case of high-sulphur coals, retention of a significant proportion of the sulphur in fixed carbon would introduce considerable error. The use of any unvarying mineral matter/ash factor may result in under or over correction of volatile matter yield, although this would have little effect on the results for very clean samples.

Using the detailed data now available, it is possible to relate volatile matter to vitrinite reflectance ($\overline{R}$o max). N. A. Newman (<u>in press</u>) has developed correction formulae for Pike River and Webb/Baynes coals, incorporating mineral matter:ash factors tailored for each sample, using ash constituents data in each case and referring to representative mineral matter analyses. For both Pike River and Webb/Baynes coals, experimentation with various sulphur-correction factors has shown that best linearity of volatile matter/vitrinite reflectance plots is achieved if half the sulphur is assumed to remain in the char. This factor has since been confirmed by direct measurement (N. A. Newman <u>in press</u>).

For Brunner coals from Pike River Coalfield the formula used in this thesis is as follows (VM = volatile matter, A = ash, S = sulphur):

$$VM\ dmm\tfrac{1}{2}sf = \frac{VM - 0.3Aa - 0.78Aca - 1.1Amg - \tfrac{1}{2}S}{100 - A - 0.3Aa - 0.78Aca - 1.1Amg - S + As} \quad \text{(all dry basis)}$$

Where Aa is the alumina component of ash (Al_2O_3% x Adb%) ÷ 100

Aca " " CaO " " " (CaO% x Adb%) ÷ 100

Amg " " MgO " " " (MgO% x Adb%) ÷ 100

As " " sulphate " " " (SO_3% x Adb%) ÷ 100

This equation can be simplified to the following:

$$VM\ dmmxsf = \frac{100\ (VMdb - \alpha - xS)}{100 - Adb - \alpha - S + As}$$

where $\alpha = 0.3Aa + 0.78Aca + 1.1Amg$

The formula is based on the following assumptions, which are supported by mineral matter analyses.

(1) Alumina occurs predominantly as kaolinite

(2) All MgO occurs as dolomite

(3) All CaO occurs as dolomite + calcite

(4) SO_3 is $CaSO_4$, predominantly formed on ashing.

For Brunner coals from Webb/Baynes the formula is:

$$VM\ dmm\tfrac{1}{2}sf = \frac{100\ (VM - 0.14\ Ak - \tfrac{1}{2}S)}{100 - 1.14\ Ak - (A-Ak) - S} \quad \text{(all dry basis)}$$

where $Ak = Ash - (Fe_2O_3 + TiO_2)$

Assumptions made are as follows:

(1) Mineral matter silicates are largely kaolinite, which is approximated by the term 0.14 Ak.

(2) Fe_2O_3 in ash is derived from pyrite, for which the sulphur contribution to volatile matter is included in the terms -S and $-\tfrac{1}{2}S$.

(3) TiO_2 in ash is derived from rutile, which makes no contribution to volatile matter.

For upper Rewanui Coals from the Rapahoe Sector the formula is:

$$VMdmm\tfrac{1}{2}sf = \frac{100(VM - \alpha - \tfrac{1}{2}s)}{100 - A - \alpha - S + As + Afe} \quad \text{(all dry basis)}$$

Where :

α = the sum of:-

$0.40(K_2O\% \times Adb) \div 100$ (illite)
$0.35(Al_2O_3' \times Adb) \div 100$ (kaolinite , where $Al_2O_3' = Al_2O_3 - 2.5K_2O$)
$0.78(CaO \times Adb) \div 100$ $(CaCO_3)$
$1.10(MgO \times Adb) \div 100$ $(MgCO_3)$
$0.55(Fe_2O_3 \times Adb) \div 100$ $(FeCO_3)$

$As = (SO_3 \times Adb) \div 100$ = sulphate (in ash) factor
$Afe = 0.1\ (Fe_2O_3)Adb$ = iron (in ash) factor

These formulae represent simplified versions of those developed in a more rigorous treatment by N. A. Newman (in press), based on mineral matter analyses.

With reference to Suggate's weathering plots relating moisture and volatile matter to carbon (Suggate 1959 p. 66) it is possible to prepare a plot relating the weathering-induced decline in volatile matter to moisture directly (Fig. 169). Suggate's plots are based on data from Buller Coalfield and appear to represent weathering of coals similar in rank to those at Pike River Coalfield.

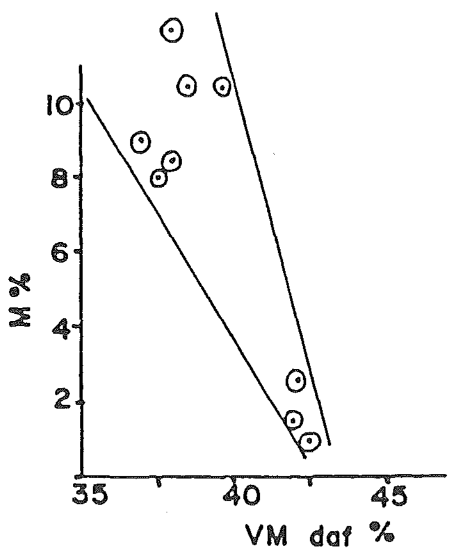


FIGURE 169. Relationship between moisture and volatile matter in increasingly weathered coal, data derived from Suggate (1959).

With reference to Figure 169, and assuming unweathered Brunner coal at Pike River Coalfield has moisture c. 1%, volatile matter is adjusted upwards 1% for every 2% increase in moisture which results from weathering. This adjustment has been applied to outcrop data used in the foregoing thesis, i.e., to analyses of Paparoa and Brunner coals from Pike River Coalfield.

ANALYSIS PRIOR TO INTRODUCTION OF THE BRITISH STANDARD METHOD

Of the samples referred to in this thesis, a few Rapahoe Sector (Greymouth) coals were analysed by CRA prior to introduction of the British Standard method of proximate analysis, by which volatile matter yield is determined at a higher temperature than CRA had used previously. Volatile matter values from such early analyses must be corrected upwards, to approximate what they would be if acquired by the new method. CRA have provided the following formula to this end: VM % new = VM% old x 0.914 + 5.577 (all dry basis).

APPENDIX 9

DETERMINATION OF ORIGINAL CLASTIC ASH VALUES FOR BRUNNER COALS FROM PIKE RIVER COALFIELD

A substantial proportion of the mineral matter in unweathered Brunner coals from Pike River Coalfield consists of authigenic carbonates and pyrite. N. A. Newman (in press) has investigated the mineralogy of the coals, and used CRA ash constituents analyses for drillhole samples to estimate original detrital ash values (Table 10), assuming that these are approximated by quartz and kaolinite content. Other minerals occur in insignificant amounts. On the basis of his results, N. A. Newman attributes a disparity between outcrop and drill-hole ash analyses to loss of carbonates and some pyrite during weathering of outcrop coal.

Drillhole	PRDH1	PRDH1	PRDH2	PRDH2	PRDH3	PRDH3	PRDH3	PRDH3	PRDH4	PRDH5	PRDH5	PRDH6	PRDH6	PRDH6
Composite	2	3	2	3	1	2	3	4	2	1	2	1	2	3
CRA No.	30/792	30/793	30/926	30/927	33/003	33/004	33/005	33/006	30/948	30/966	33/044	30/971	30/985	33/045
Ash % air dried	5.3	2.4	4.2	3.1	4.8	3.5	3.0	2.7	3.9	5.5	7.2	7.0	3.1	5.1
CaO %	21.3	29.6	16.6	32.1	15.1	38.2	28.5	24.4	20.7	26.5	16.4	16.9	20.0	11.0
MgO %	11.5	16.2	11.9	20.7	8.2	19.9	18.9	22.4	10.8	17.2	9.2	3.7	14.0	7.0
Fe_2O_3 %	26.3	8.3	26.7	4.6	27.7	4.3	9.6	3.8	13.0	8.2	20.7	42.9	16.9	3.5
SO_3 %	30.8	34.3	22.8	27.8	20.1	22.0	34.6	24.4	29.6	34.1	27.1	22.9	27.8	11.0
CaO' % (1)	30.8	45.0	21.5	44.5	18.9	48.9	43.6	47.2	29.4	40.2	22.5	21.9	22.7	12.4
MgO' % (1)	16.6	24.7	15.4	28.7	10.3	25.5	28.9	29.6	15.3	26.1	12.6	4.8	19.4	7.9
Fe_2O_3' % (1)	38.0	12.6	34.7	6.4	34.7	5.5	14.7	5.0	18.5	12.4	28.4	55.6	23.4	3.9
"Fe in coke" %	2.4	0.3	1.9	0.2	2.3	0.3	0.5	0.2	0.9	0.4	1.5	3.0	0.5	0.2
Excess CaO % (2)	7.4	10.2	0.6	1.6	4.4	13.0	2.9	5.5	7.9	3.4	4.8	15.1	1.2	1.3
(CaO + MgO) in coal % (3)	1.7	1.1	1.2	4.1	1.1	2.0	1.4	1.5	1.2	2.4	1.8	1.4	1.0	0.9
Ash - Carbonates % (4)	1.93	0.46	2.10	0.60	2.70	0.67	0.54	0.49	1.52	1.22	3.41	3.96	1.18	3.55
Ash - Carbonates & Pyrite % (5)	0.53	0.26	0.98	0.47	1.37	0.52	0.25	0.39	1.01	0.77	1.92	0.96	0.66	3.37

(1) Calculated to sulphate-free basis

(2) Excess CaO over pure dolomite composition

(3) Carbonate oxide content of coal $= \left\{\frac{\text{CaO} + \text{MgO}}{100}\right\} \times \text{A}\%$

(4) (Ash - Carbonate components) $= \text{A} - \left[\left\{\frac{\text{CaO} + \text{MgO} + \text{SO}_3}{100}\right\} \times \text{A}\right] \%$

(5) Ash (Carbonate + Pyrite components) $= \text{A} - \left[\left\{\frac{\text{CaO} + \text{MgO} + \text{SO}_3 + \text{Fe}_2\text{O}_3}{100}\right\} \times \text{A}\right] \%$

TABLE 11 Use of ash constituents data to calculate original detrital ash and other properties.
(From N. A. & J. Newman, Appendix 2 in Newman, J. 1984b)